Open-Source Software for Power Industry Research, Teaching, and Training

---

A DC Optimal Power Flow Illustration

Leigh Tesfatsion

Professor of Economics

Courtesy Professor of Mathematics

Iowa State University, Ames, IA 50011

https://www2.econ.iastate.edu/tesfatsi/

tesfatsi@iastate.edu

IEEE Power Engineering Society
General Meeting, 27 June 2007

(Formatting Updated 3/13/2024)

Acknowledgement

The research reported in this presentation constitutes part of the

AMES Market Project

https://www2.econ.iastate.edu/AMESMarketHome.htm

Project Director: **Leigh Tesfatsion** (Prof of Econ, Courtesy Prof. of Math, ISU)

Research Associate: **Junjie Sun** (Financial Economist, OCC, U.S. Treasury, Wash, D.C.)

Research Assistant: **Hongyan Li** (PhD. Cand, Electrical & Comp Eng., ISU)

funded in part by the

National Science Foundation and the
ISU Electric Power Research Center

Presentation Outline

- Why **O**pen-**S**ource **S**oftware (**OSS**) for wholesale power markets?
- **DCOPFJ**: A **DC O**ptimal **P**ower **F**low solver (in **J**ava)

  DCOPFJ Home Page (Code Release Site)
  https://www2.econ.iastate.edu/tesfatsi/DCOPFJHome.htm

- DCOPFJ Illustration: A Simple 3-Node Test Case
- Release of DCOPFJ as free OSS
- Incorporation of DCOPFJ into the AMES (Java) software package

  Agent-Based **M**odeling of **E**lectricity **S**ystems (**AMES**)
  https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- Conclusion

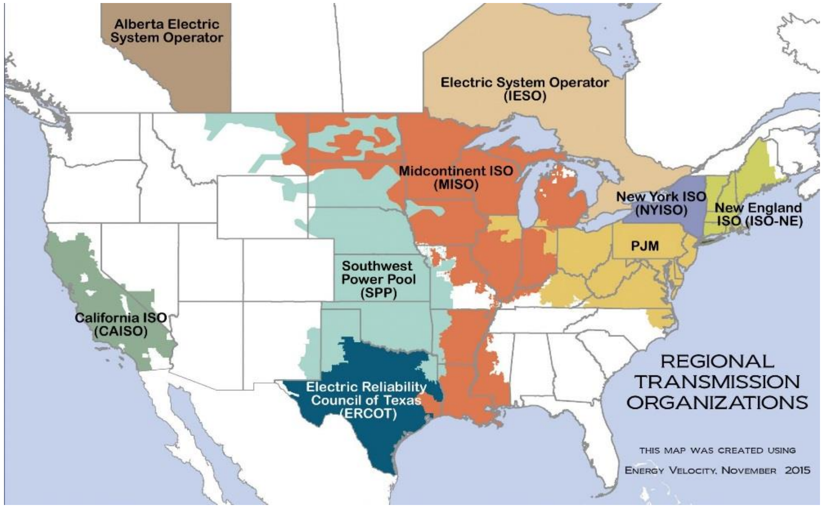
Why OSS for Wholesale Power Markets?

- In April 2003, the U.S. Federal Energy Regulatory Commission (FERC) proposed a **W**holesale **P**ower **M**arket **P**latform **(WPMP)** for common adoption by all U.S. wholesale power markets.

- Over 60% of U.S. electric power generating capacity is now operating under some version of the WPMP market design.

North American Regions Adopting Versions of WPMP Design as of 2015

https://www.ferc.gov/industries/electric/indus-act/rto/rto-map.asp



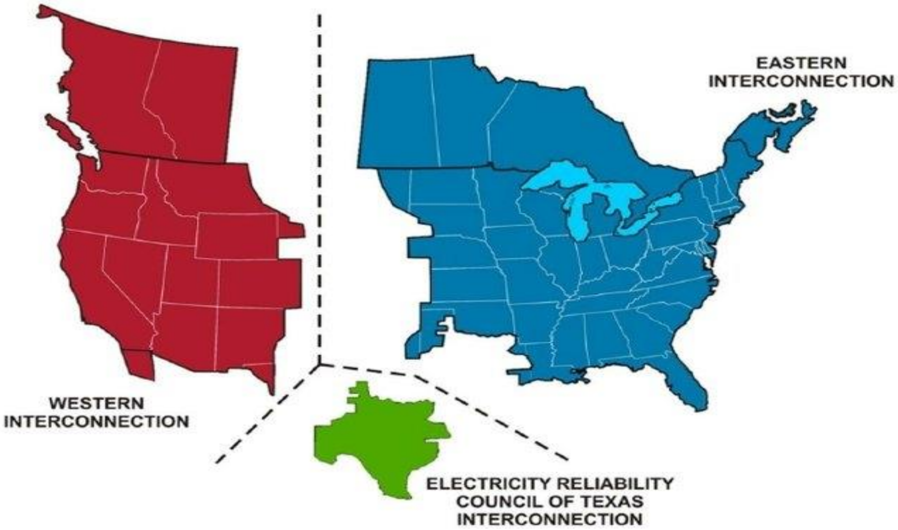


Fig. 1: *Seven North-American RTO/ISO-managed wholesale power markets operate over a high-voltage AC transmission grid consisting of three separately-synchronized parts.*

Features Generally Shared by These Restructured Wholesale Power Markets

- Their market designs are **complicated!**
- Managed by an **I**ndependent **S**ystem **O**perator (**ISO**) or a **R**egional **T**ransmission **O**rganization (**RTO**)
- Day-ahead & real-time markets for power
- Transmission grid congestion managed via some variant of **L**ocational **M**arginal **P**ricing (**LMP**)
- Prices/power levels typically determined by ISO/RTO as solutions to **DC O**ptimal **P**ower **F**low **(DC-OPF)** problems

Software Availability

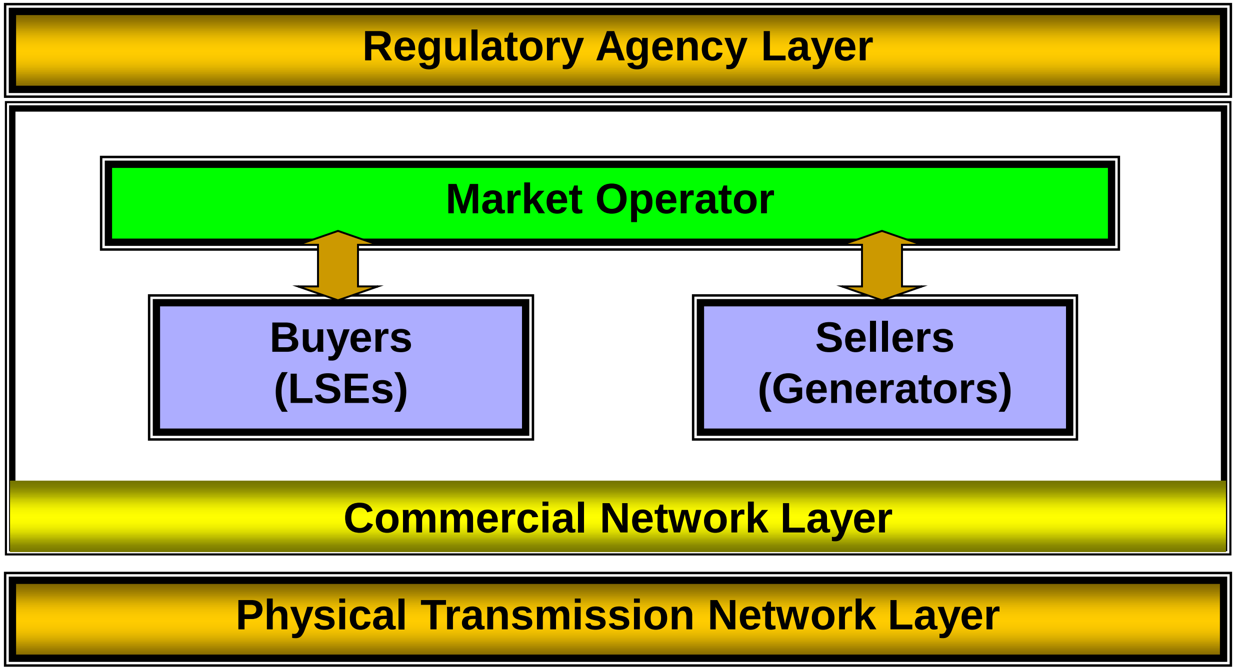
- Many commercial packages now include components suitable for the simulation of restructured wholesale power markets.

- However, lack of open-source access:
  - prevents accurate understanding of implementation;
  - restricts experimentation with new features;
  - hinders tailoring software to specific needs;

Resource Site for Electric Power Market OSS

OSS for Electricity Market Research, Teaching, and Training

https://www2.econ.iastate.edu/tesfatsi/ElectricOSS.htm



Postings at this Site: Examples

- Market Simulators
  - AMES Market Package (Java) – Sun, Li, Tesfatsion
  - JASA Class Library (Java) – S. Phelps

- **O**ptimal **P**ower **F**low (**OPF**) Solvers
  - DCOPFJ (Java) -- J. Sun & L. Tesfatsion
  - MATPOWER (Matlab-based) -- R. Zimmermann et al.
  - PSAT (Matlab-based) -- F. Milano

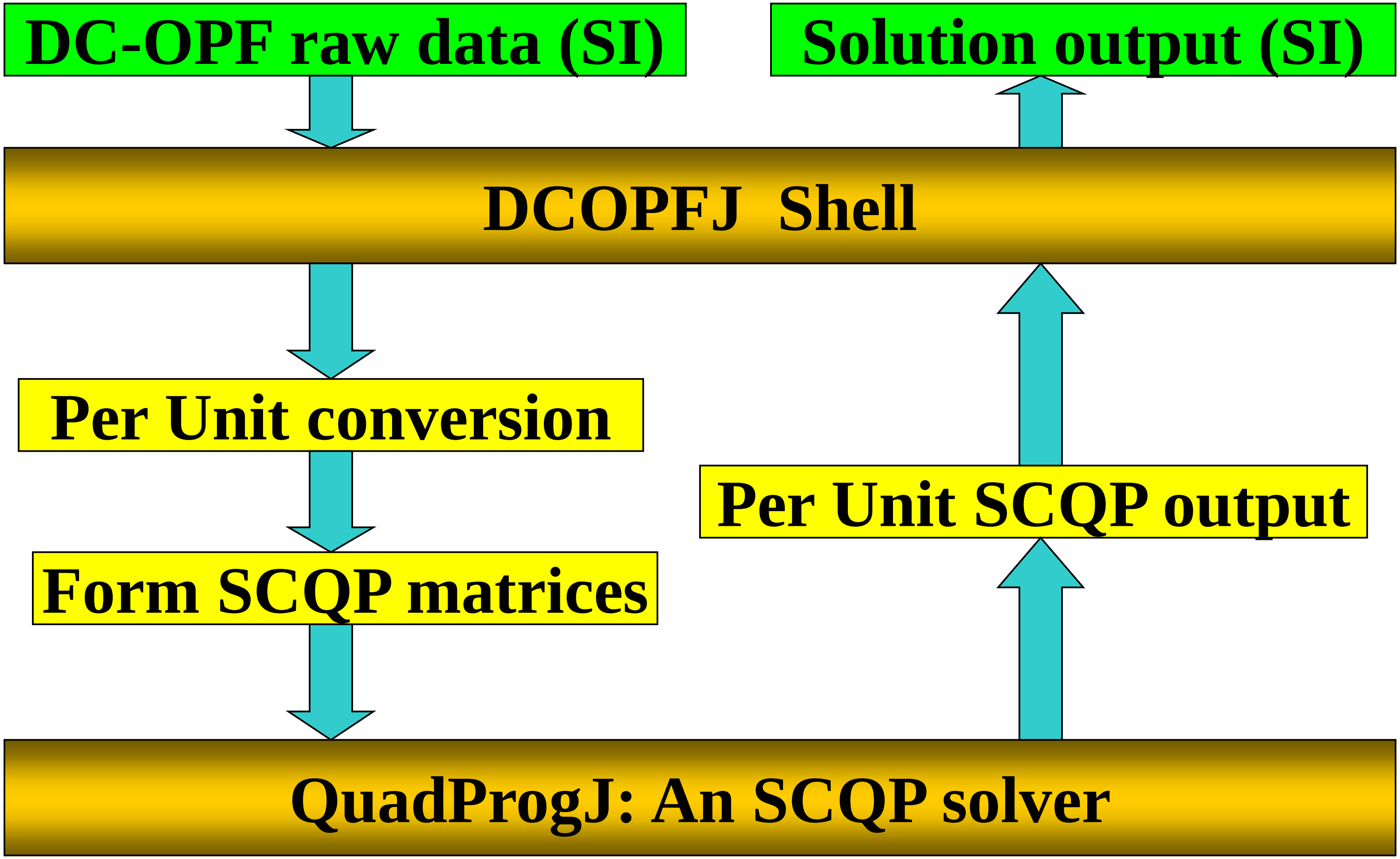
DCOPFJ: A Java DC-OPF Solver

Sun & Tesfatsion, *Proceedings*, IEEE PES GM 2007

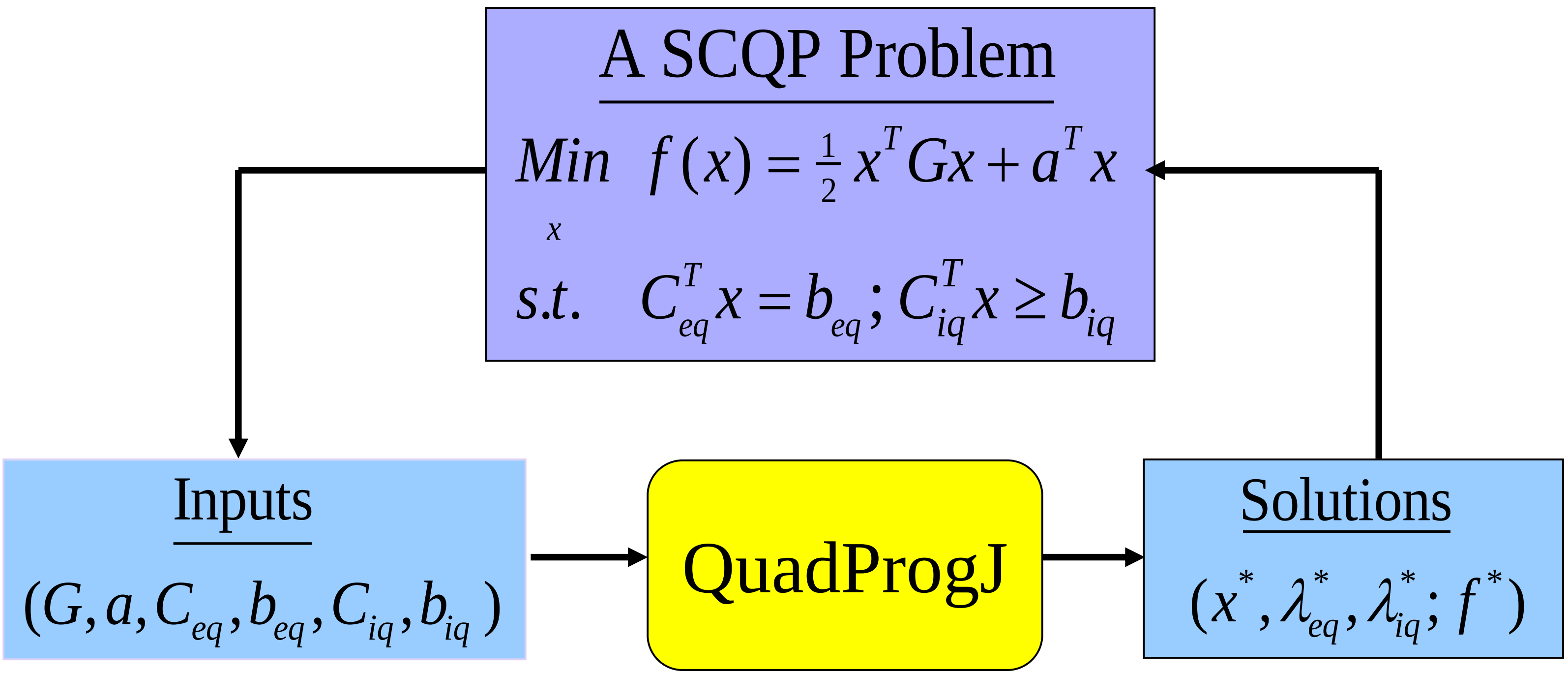
https://www2.econ.iastate.edu/tesfatsi/DCOPFJHome.htm

- Standard DC-OPF problems can usefully be augmented by a soft penalty function that controls the size of squared voltage angle differences.
- Such augmented DC-OPF problems can be formulated as **S**trictly **C**onvex **Q**uadratic **P**rogramming (**SCQP**) problems.
- SCQP problems can be solved by **QuadProgJ,** a stable accurate Java SCQP solver incorporated into DCOPFJ.
- The **DCOPFJ shell** transforms augmented DC-OPF input data from **S**tandard **I**nternational (**SI**) form to **P**er-**U**nit (**PU**) form, fills matrices needed by QuadProgJ, invokes QuadProgJ, and returns solution output in SI form.

DCOPFJ: A DC-OPF Solver (Java)



QuadProgJ: A Java SCQP Solver Incorporated Into DCOPFJ



Brief Description of QuadProgJ

(Sun/Tesfatsion, ISU Econ WP #06025, Revised 7/07)

- Appears to be the **first open-source Java SCQP solver**
- Implements the well-known dual active-set SCQP algorithm developed by Goldfarb and Idnani (1983)
- Can be used as a stand-alone SCQP solver or as a plug-and-play SCQP solution module
- Numerically stable (uses Cholesky decomposition, QR factorization, etc.)
- Accuracy tested on a repository of small-to-medium-sized SCQP problems.
- Performance matches or exceeds that of BPMPD, a well-known **proprietary** C-language QP solver recommended highly in the *MATPOWER User's Manual*

Repository of QP Min Problems with BPMPD Solutions

(TN = Total Number of Constraints Plus Decision Variables)

Table 3: SCQP Test Cases: Structural Attributes and BPMPD Solution Values

NAME[a]	TND[b]	TNEC[c]	TNIC[d]	TNC[e]	TN[f]	fBPMPD[g]
DUAL1	85	1	170	171	256	3.50129662E-02
DUAL2	96	1	192	193	289	3.37336761E-02
DUAL3	111	1	222	223	234	1.35755839E-01
DUAL4	75	1	150	151	226	7.46090842E-01
DUALC1	9	1	232	233	242	6.15525083E+03
DUALC5	8	1	293	294	302	4.27232327E+02
HS118	15	0	59	59	74	6.64820452E+02
HS21	2	0	5	5	7	-9.99599999E+01
HS268	5	0	5	5	10	5.73107049E-07
HS35	3	0	4	4	7	1.11111111E-01
HS35MOD	3	0	5	5	8	2.50000001E-01
HS76	4	0	7	7	11	-4.68181818E+00
KSIP	20	0	1001	1001	1021	5.757979412E-01
QPCBLEND	83	43	114	157	240	-7.84254092E-03
QPCBOEI1	384	9	971	980	1364	1.15039140E+07
QPCBOEI2	143	4	378	382	525	8.17196225E+06
QPCSTAIR	467	209	696	905	1372	6.20438748E+06
S268	5	0	5	5	10	5.73107049E-07
MOSARQP2	900	0	600	600	1500	-0.159748211E+04

RD = [QuadProg – BPMPD]/|BPMPD|

(All Test Cases Run on a Laptop PC operating under Win XP SP2)

Table 4: QuadProgJ Test Case Results

NAME	Mean|ECE|[a]	Max|ECE|[b]	NVIC[c]	f*[d]	RD[e]
DUAL1	0.0	0.0	0	3.50129657E-2	-1.42804239E-8
DUAL2	0.0	0.0	0	3.37336761E-2	0.0
DUAL3	6.66E-16	6.66E-16	0	1.35755837E-1	-1.47323313E-8
DUAL4	2.11E-15	2.11E-15	0	7.46090842E-1	0.0
DUALC1	2.40E-12	2.40E-12	0	6.15525083E+3	0.0
DUALC5	5.33E-15	5.33E-15	0	4.27232327E+2	0.0
HS118	NA[f]	NA	0	6.64820450E+2	-3.00833103E-9
HS21	NA	NA	0	-99.96	-1.00040010E-9
HS268	NA	NA	0	-5.47370291E-8	-1.09550926
HS35	NA	NA	0	1.11111111E-1	0.0
HS35MOD	NA	NA	0	2.50000000E-1	-4.00000009E-9
HS76	NA	NA	0	-4.68181818	0.0
KSIP	NA	NA	0	5.75797941E-1	0.0
QPCBLEND	5.66E-16	8.94E-15	0	-7.84254307E-3	-2.74145844E-7
QPCBOEI1	2.05E-6	9.58E-6	0	1.15039140E+7	0.0
QPCBOEI2	3.42E-6	1.37E-5	0	8.17196224E+6	-1.22369628E-9
QPCSTAIR	4.34E-7	6.01E-6	0	6.20438745E+6	-4.83528799E-9
S268	NA	NA	0	-5.47370291E-8	-1.09550926
MOSARQP2	NA	NA	--	Out of Memory Error	—

Augmented DC-OPF Problem (SI) with LSE Fixed Demand Bids

Generator total variable costs

(Solved by DCOPFJ-Version 1.1)

Voltage angle for node k

$$\text{Minimize} \quad \sum_{i=1}^{I} [A_i \, p_{Gi} + B_i \, p_{Gi}^2] + \pi \left[\sum_{km \in BR} [\delta_k - \delta_m]^2 \right]$$

w.r.t. $\quad p_{Gi}, i = 1, \ldots, I; \quad \delta_k, k = 1, \ldots, K$

Power level for Generator i=1,…,I

subject to

Balance constraints:

Shadow price for node k balance constraint gives LMP for node k

$$0 = \sum_{j \in J_k} p_{Lj} - \sum_{i \in I_k} p_{Gi} + \sum_{km \text{ or } mk \in BR} y_{km}(\delta_k - \delta_m)$$

Fixed demand bid (load) for LSE j

Branch flow (thermal) constraints:

$$| y_{km}(\delta_k - \delta_m) | \leq F^U_{km}$$

Reported production capacity constraints:

$$P^L_{Gi} \leq p_{Gi} \leq P^U_{Gi}$$

Shadow price for each inequality constraint is also determined

Voltage angle setting at reference node 1:

$$\delta_1 = 0$$

Augmented DC-OPF Problem (SI) with LSE Fixed and/or Price-Sensitive Demand Bids (Solved by DCOPFJ - Version 2.0)

Minimize

$$\sum_{i=1}^{I}[a_i p_{Gi} + b_i p_{Gi}^2] - \sum_{j=1}^{J}[c_j p_{Lj}^S - d_j {p_{Lj}^S}^2] + \pi \left[\sum_{km \in BR} [\delta_k - \delta_m]^2 \right]$$

LSE gross buyer surplus

Generator total variable costs

w.r.t. $\quad p_{Gi},\ i = 1, ..., I;\ p_{Lj}^S,\ j = 1, ..., J;\ \delta_k,\ k = 1, ..., K$

Subject to

$$\sum_{i \in I_k} p_{Gi} - \sum_{j \in J_k} (p_{Lj}^F + p_{Lj}^S) - \sum_{km \text{ or } mk \in BR} y_{km} [\delta_k - \delta_m] = 0$$

$$|y_{km} [\delta_k - \delta_m]| \le F^U{}_{km}$$

$$P^L{}_{Gi} \le p_{Gi} \le P^U{}_{Gi}$$

$$SLoad_j^L \le p_{Lj}^S \le SLoad_j^U$$

$$\delta_1 = 0$$

Fixed and price-sensitive demand bids for LSE j

Augmented DC-OPF Problem in SCQP Form Suitable for QuadProgJ

(Same general form for fixed or price-sensitive demand)

Minimize

$$f(x) = \frac{1}{2}x^T G x + a^T x$$

with respect to

$$x = (x_1, x_2, \ldots, x_M)^T$$

subject to

$$C_{eq}^T x = b_{eq}$$

$$C_{iq}^T x \geq b_{iq}$$

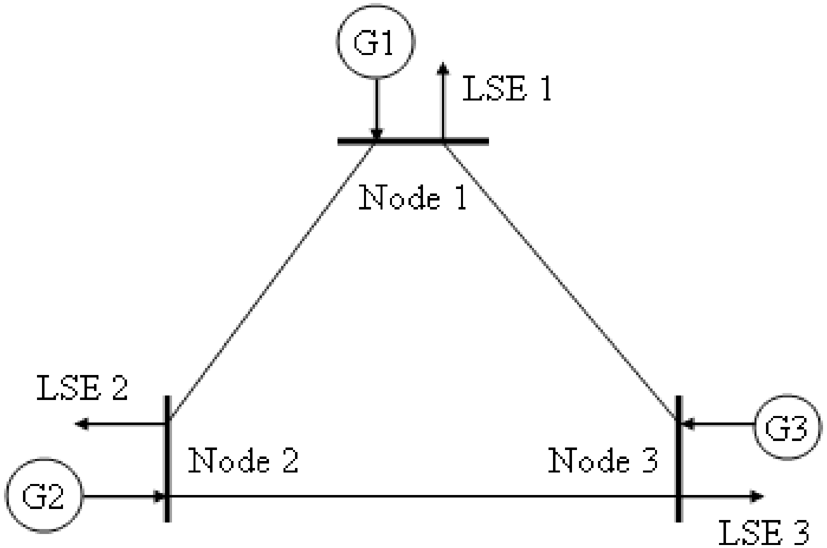
where **G** is an **M**×**M** symmetric positive definite matrix.

DCOPFJ Illustration: A Simple 3-Node Test Case

- A 3-node DC-OPF problem with LSE fixed demand bids (no price-sensitive demand)
- DC-OPF problem for each hour formulated as a matrix SCQP Problem: $(x, G, a, C_{eq}, b_{eq}, C_{iq}, b_{iq})$
- DC-OPF solutions for 24 successive hours obtained by DCOPFJ (Version 1.1) through invocation of its internal SCQP solver QuadProgJ
- Unit conversions (SI-to-PU-to-SI) omitted for expositional simplicity

Transmission Grid for 3-Node Test Case

A 3-Node Transmission Grid



24-Hour DC-OPF Input Data (SI) for 3-Node Test Case

Base Values

S_o	V_o
100	10

K	π
3	0.05

Branch

From	To	F^U_{km}	Reactance x_{km}
1	2	55	0.20
1	3	55	0.40
2	3	55	0.25

Gen

ID	atNode	FCost	Cost Parameters A_i,B_i		P_{Gi}^L	P_{Gi}^U
1	1	14	10.6940	0.00463	20	200
2	2	21	18.1000	0.00612	10	150
3	3	11	37.8896	0.01433	5	20

LSE Hourly Loads P_{Lj}

ID	atNode	L-0[illegible]	L-02	L-03	L-04	L-05	L-06	L-07	L-08
1	1	132.66	122.4	115.62	112.2	108.84	110.52	112.2	119.04
2	2	44.22	40.8	38.54	37.4	36.28	36.84	37.4	39.68
3	3	44.22	40.8	38.54	37.4	36.28	36.84	37.4	39.68
ID	atNode	L-09	L-10	L-11	L-12	L-13	L-14	L-15	L-16
1	1	136.02	149.64	153.06	154.74	153.06	149.64	147.96	147.96
2	2	45.34	49.88	51.02	51.58	51.02	49.88	49.32	49.32
3	3	45.34	49.88	51.02	51.58	51.02	49.88	49.32	49.32
ID	atNode	L-17	L-18	L-19	L-20	L-21	L-22	L-23	L-24
1	1	154.74	170.04	163.26	161.52	159.84	156.42	147.96	137.76
2	2	51.58	56.68	54.42	53.84	53.28	52.14	49.32	45.92
3	3	51.58	56.68	54.42	53.84	53.28	52.14	49.32	45.92

Three Node Test Case … Continued

SCQP Matrices/Vectors

$(x, G, a, C_{eq}, b_{eq}, C_{iq}, b_{iq})$

$$\mathbf{x} \;=\; [P_{G1}, P_{G2}, P_{G3}, \delta_2, \delta_3]^{\mathbf{T}}_{(5\times 1)}$$

$$\mathbf{G} = \begin{bmatrix} 2B_1 & 0 & 0 & 0 & 0 \\ 0 & 2B_2 & 0 & 0 & 0 \\ 0 & 0 & 2B_3 & 0 & 0 \\ 0 & 0 & 0 & 4\;2 & \text{-}2\pi \\ 0 & 0 & 0 & \text{-}2\pi\;) & 4\;2\;\;{}_3 \end{bmatrix}_{(5\times 5)}$$

$$\mathbf{a}^{\mathbf{T}} = [\; A_1 \quad A_2 \quad A_3 \quad 0 \quad 0 \;]_{(1\times 5)}$$

$$\mathbf{C}_{\mathbf{eq}}^{\mathbf{T}} = \begin{bmatrix} 1 & 0 & 0 & y_{12} & y_{13} \\ 0 & 1 & 0 & -(y_{12}+y_{23}) & y_{23} \\ 0 & 0 & 1 & y_{23} & -(y_{13}+y_{23}) \end{bmatrix}_{(3\times 5)}$$

$$\mathbf{b}_{\mathbf{eq}} = \begin{bmatrix} P_{L1} & P_{L2} & P_{L3} \end{bmatrix}_{(3\times 1)}^{\mathbf{T}}$$

$y_{km} = 1/x_{km}$

$$\mathbf{C}_{\mathbf{iq}}^{\mathbf{T}} = \begin{bmatrix} 0 & 0 & 0 & y_{12} & 0 \\ 0 & 0 & 0 & 0 & y_{13} \\ 0 & 0 & 0 & -y_{23} & y_{23} \\ 0 & 0 & 0 & -y_{12} & 0 \\ 0 & 0 & 0 & 0 & -y_{13} \\ 0 & 0 & 0 & y_{23} & -y_{23} \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \end{bmatrix}_{(12\times 5)}$$

$$\mathbf{b}_{\mathbf{iq}} = \begin{bmatrix} -F_{12}^{U} & -F_{13}^{U} & -F_{23}^{U} & -F_{12}^{U} & -F_{13}^{U} & -F_{23}^{U} & P_{G1}^{L} & P_{G2}^{L} & P_{G3}^{L} & -P_{G1}^{U} & -P_{G2}^{U} & -P_{G3}^{U} \end{bmatrix}_{(12\times 1)}^{\mathbf{T}}$$

DCOPFJ Solution Output (SI) for 3-Node Test Case

Hour	p^*_{G1}	p^*_{G2}	p^*_{G3}	δ^*_2	δ^*_3	LMP_1	LMP_2	LMP_3	minTVC
01	200.0	16.1	5.0	-0.0799	-0.1095	18.30	18.30	18.30	2993.95
02	189.0	10.0	5.0	-0.0808	-0.1048	12.44	12.44	12.44	2724.33
03	177.7	10.0	5.0	-0.0752	-0.0979	12.34	12.34	12.34	2565.12
04	172.0	10.0	5.0	-0.0724	-0.0944	12.29	12.29	12.29	2485.70
05	166.4	10.0	5.0	-0.0696	-0.0910	12.23	12.23	12.23	2408.27
06	169.2	10.0	5.0	-0.0710	-0.0927	12.26	12.26	12.26	2446.91
07	172.0	10.0	5.0	-0.0724	-0.0944	12.29	12.29	12.29	2485.70
08	183.4	10.0	5.0	-0.0780	-0.1014	12.39	12.39	12.39	2645.13
09	200.0	21.7	5.0	-0.0741	-0.1077	18.37	18.37	18.37	3097.90
10	200.0	44.4	5.0	-0.0506	-0.1002	18.64	18.64	18.64	3527.13
11	200.0	50.1	5.0	-0.0447	-0.0983	18.71	18.71	18.71	3636.90
12	200.0	52.9	5.0	-0.0418	-0.0974	18.75	18.75	18.75	3691.11
13	200.0	50.1	5.0	-0.0447	-0.0983	18.71	18.71	18.71	3636.90
14	200.0	44.4	5.0	-0.0506	-0.1002	18.64	18.64	18.64	3527.13
15	200.0	41.6	5.0	-0.0535	-0.1011	18.61	18.61	18.61	3473.51
16	200.0	41.6	5.0	-0.0535	-0.1011	18.61	18.61	18.61	3473.51
17	200.0	52.9	5.0	-0.0418	-0.0974	18.75	18.75	18.75	3691.11
18	200.0	78.4	5.0	-0.0154	-0.0890	19.06	19.06	19.06	4193.64
19	200.0	67.1	5.0	-0.0271	-0.0927	18.92	18.92	18.92	3968.98
20	200.0	64.2	5.0	-0.0301	-0.0937	18.89	18.89	18.89	3911.83
21	200.0	61.4	5.0	-0.0330	-0.0946	18.85	18.85	18.85	3856.85
22	200.0	55.7	5.0	-0.0389	-0.0965	18.78	18.78	18.78	3745.51
23	200.0	41.6	5.0	-0.0535	-0.1011	18.61	18.61	18.61	3473.51
24	200.0	24.6	5.0	-0.0711	-0.1067	18.40	18.40	18.40	3152.03

Release of DCOPFJ as Free Java OSS:
The DCOPFJ Package

- DCOPFJ is implemented as a stand-alone Java DC-OPF solver by the DCOPFJ Package.

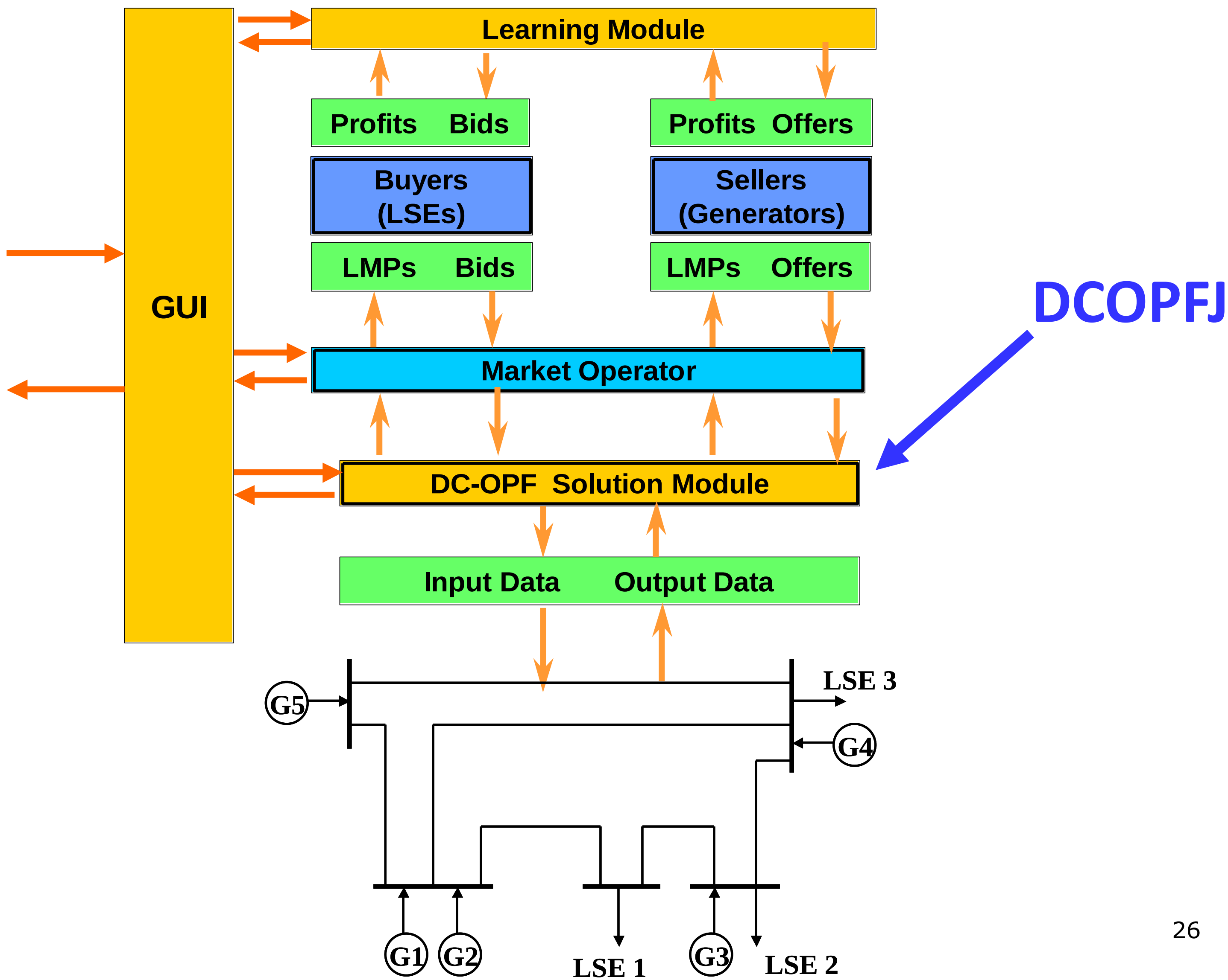
- Versions 1.1 and 2.0 of the DCOPFJ Package have been released as free open-source software under the terms of the GNU General Public License (GPL).

- **For software downloads, manuals, and research pubs, visit:**

DCOPFJ Package Home Page:

https://www2.econ.iastate.edu/tesfatsi/DCOPFJHome.htm

Incorporation of DCOPFJ into the AMES Market Package (Java OSS)



AMES Market Project

(AMES = Agent-based Modeling of Electricity Systems)

- **Development of an Agent-Based Wholesale Power Market Test Bed**

- **Implemented by AMES Market Package (free OSS Java)**
  https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- **Target Package Features**

  - **Research/teaching grade test-bed** (2-500 pricing nodes)
  - **Operational validity** (structure, rules, behavioral dispositions)
  - Permits **dynamic** testing with **learning traders**
  - Permits **intensive experimentation** with alternative scenarios
  - **Free open-source Java implementation** (full access to code)
  - **Easily modified** (extensible/modular architecture)

Key Components of the AMES Market Test-Bed

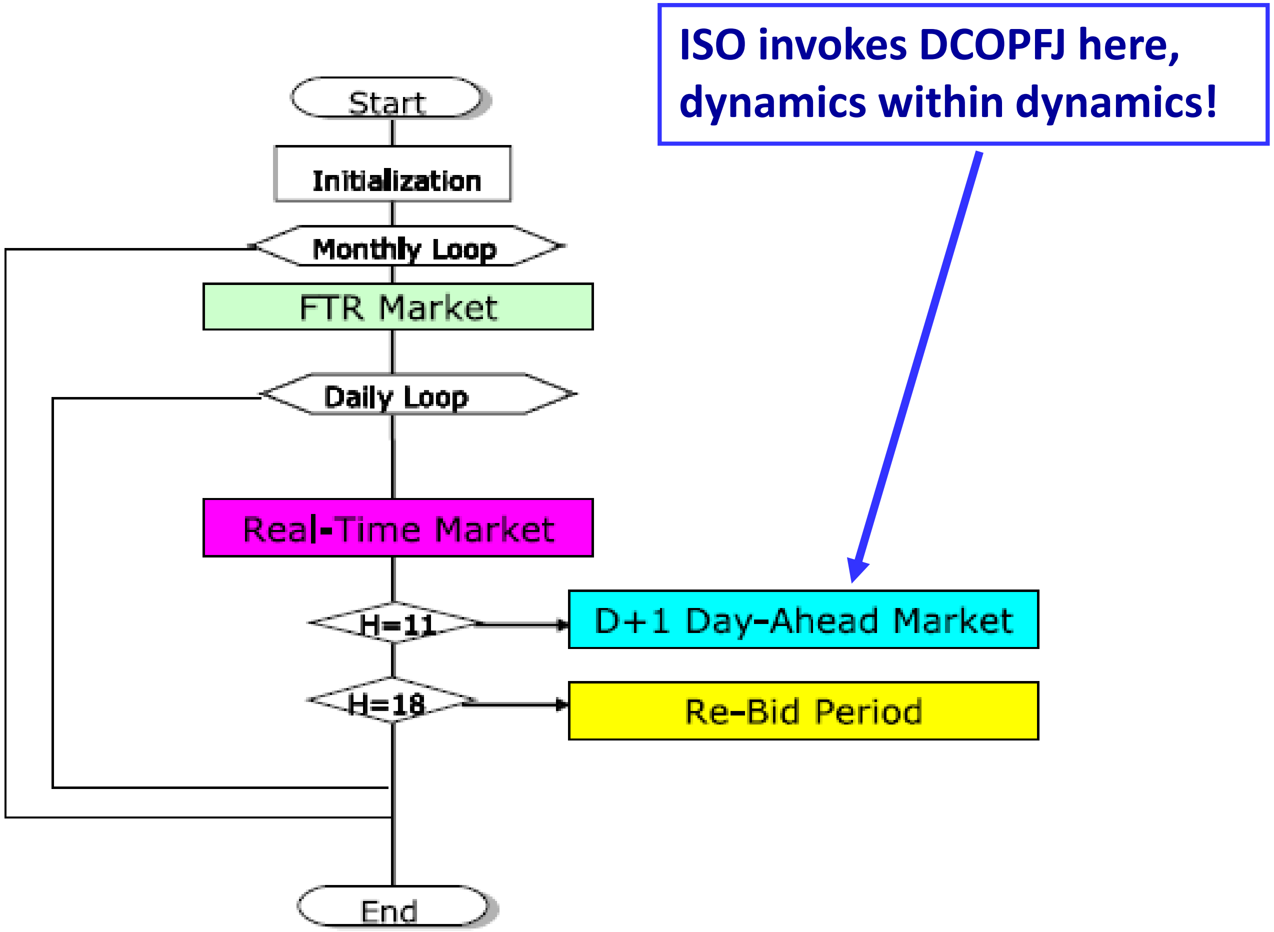
(Based on Business Practices Manuals for MISO/ISO-NE)

- **Traders**
  - Sellers and buyers
  - Follow market rules
  - **Learning abilities**
- **Independent System Operator (ISO)**
  - System reliability assessments
  - Day-ahead bid-based unit commitment **(via DC OPF)**
  - Real-time dispatch

DCOPFJ

- **Two-settlement process**
  - Day-ahead market (double auction, financial contracts)
  - Real-time market (settlement of differences)
- **AC transmission grid**
  - Sellers/buyers located at various transmission nodes
  - Congestion managed via Locational Marginal Pricing (LMP)

AMES Market Dynamics: Broad Overview



Conclusion

- Most simulation software available today for restructured electricity markets is proprietary.

- Open-source software is important for facilitating the rigorous performance study of these markets.

- It is hoped the free open-source release of DCOPFJ and the AMES Market Package will encourage the development of open-source software permitting the systematic performance study of restructured electricity market designs.

Resource Links for Electricity Market Open-Source Software (OSSO

- **OSS for Electricity Market Research, Teaching, and Training**

  https://www2.econ.iastate.edu/tesfatsi/ElectricOSS.htm

- **The *AMES* Market Package: A Free OSS Test-Bed for the *A*gent-based *M*odeling of *E*lectricity *S*ystems (Java)**

  https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- **DCOPFJ: A Free OSS Solver for DC Optimal Power Flow Problems (Java)**

  https://www2.econ.iastate.edu/tesfatsi/DCOPFJHome.htm