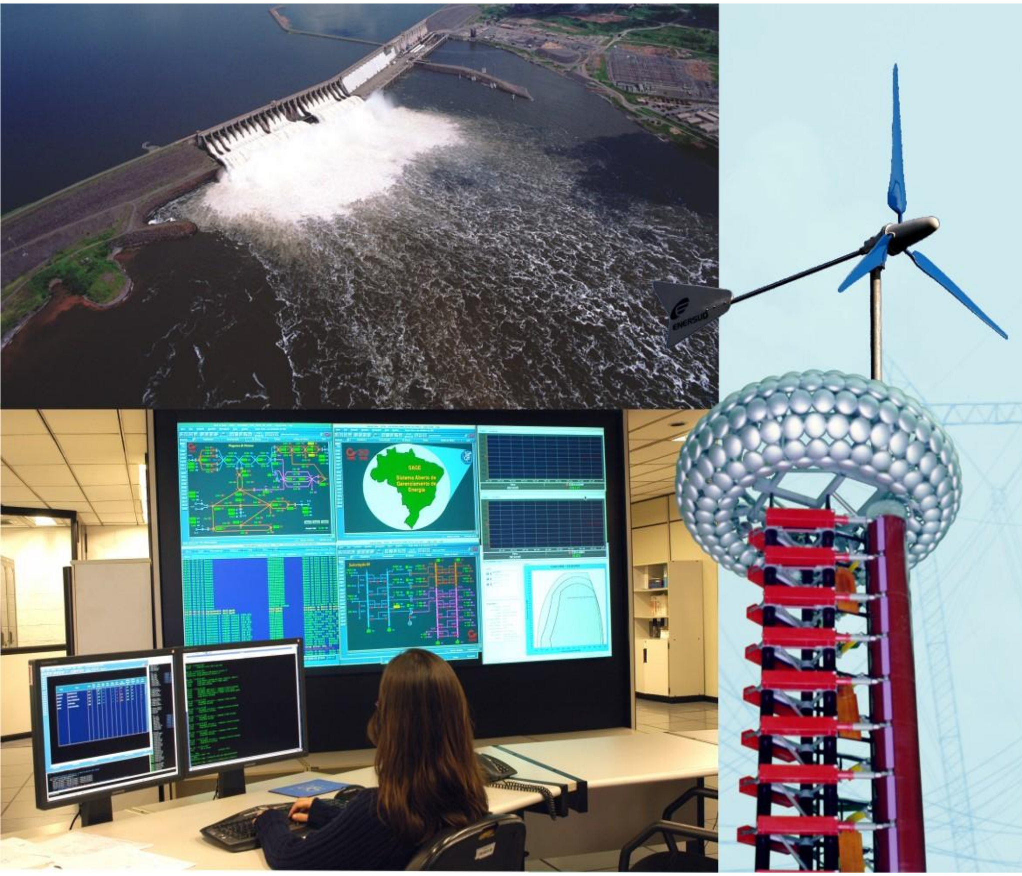


Network constrained hydrothermal unit commitment problem for hourly dispatch and price setting in Brazil: the DESSEM model

Stavanger, Norway,
Sept. 12th, 2018

André Luiz Diniz

CEPEL – Electric Energy Research Center - Rio de Janeiro, Brazil

MOTIVATION AND OUTLINE

Eletrobras Cepel

CONTEXT

- ✓ In the Brazilian system, since 2000 the dispatch has been centrally coordinated by the ISO (ONS) and market prices have been set by the Market Operator (CCEE) with the optimization tools based on dual dynamic programming, developed by CEPEL
- ✓ Many new features have been included and validated ever since
- ✓ The price is currently set by each week, in three load blocks,

MOTIVATION

- ✓ In Sept 2017 the so-called "hourly price" process was launched, in order to validate the DESSEM model for the day-ahead dispatch in half-an-hour time steps, and to obtain hourly market prices

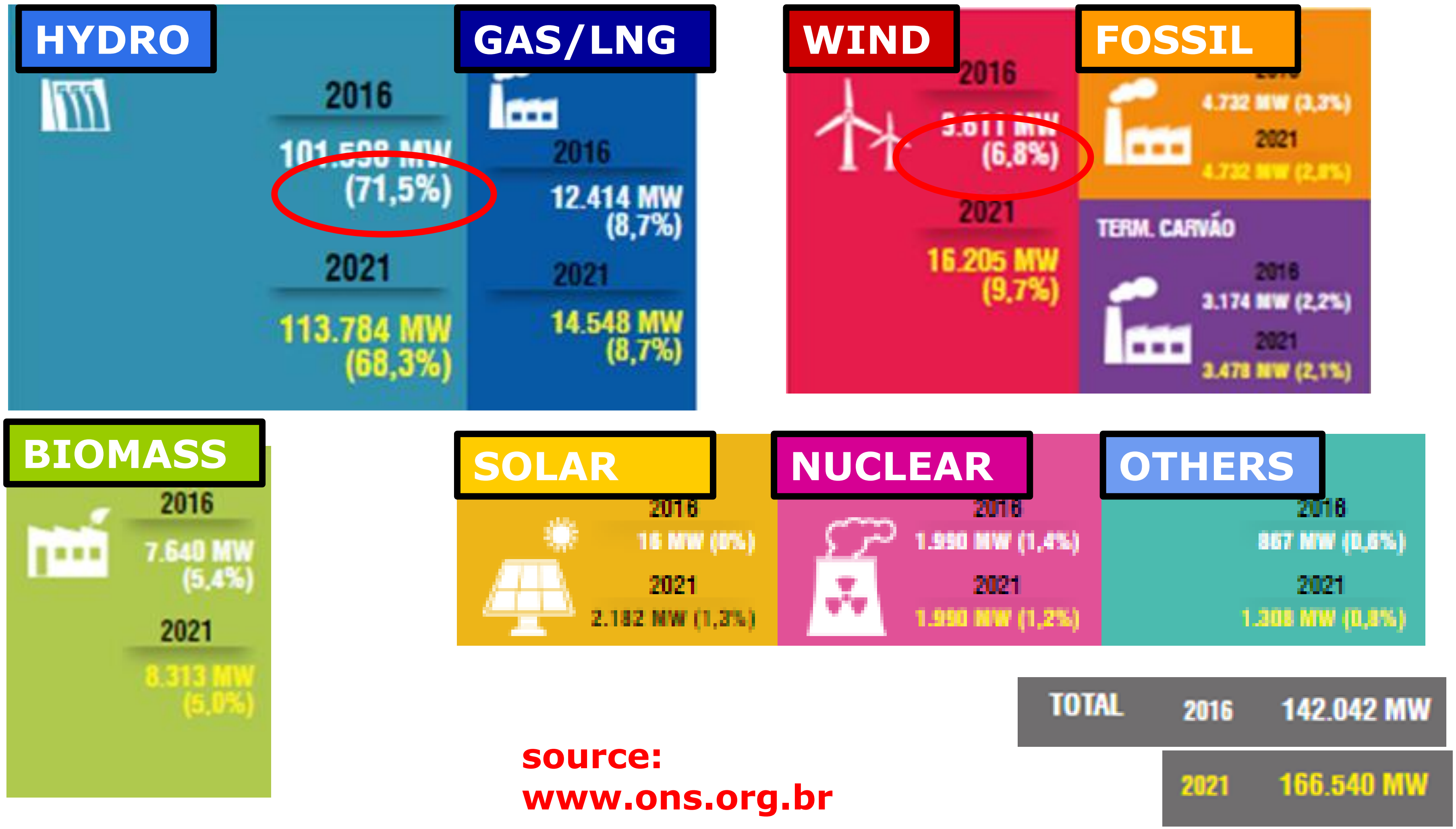
OBJECTIVE

- ✓ We present the main features of the DESSEM model and practical aspects related to its use, which is planned for January 2020.

BRAZILIAN INTERCONNECTED SYSTEM (SIN)

Eletrobras Cepel

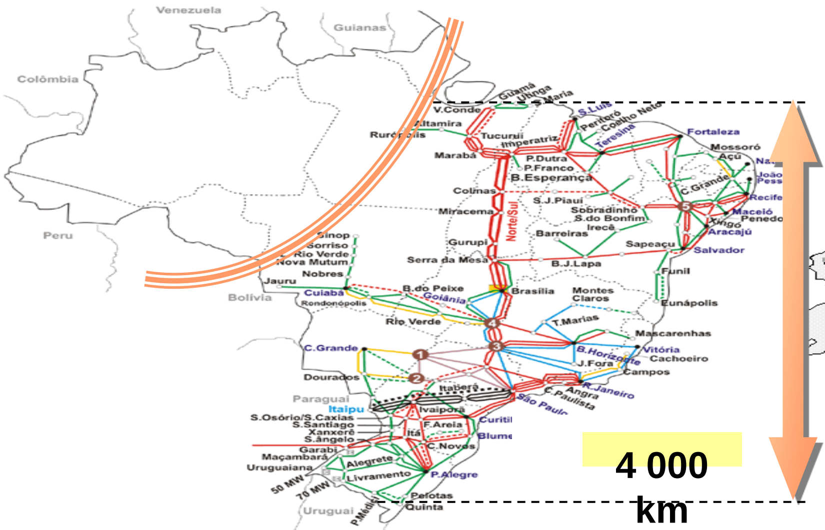
GENERATION MIX – 2016 & 2021

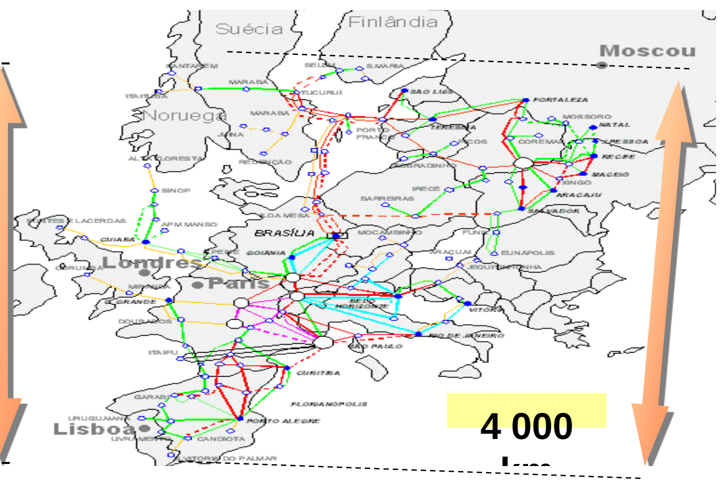


source: www.ons.org.br

MAIN CHARACTERISTICS OF THE BRAZILIAN SYSTEM

- Large-scale system, predominantly hydro
- Stochastic inflows to reservoirs
- Long distances between generation sources and load
- Many hydro plants in cascade

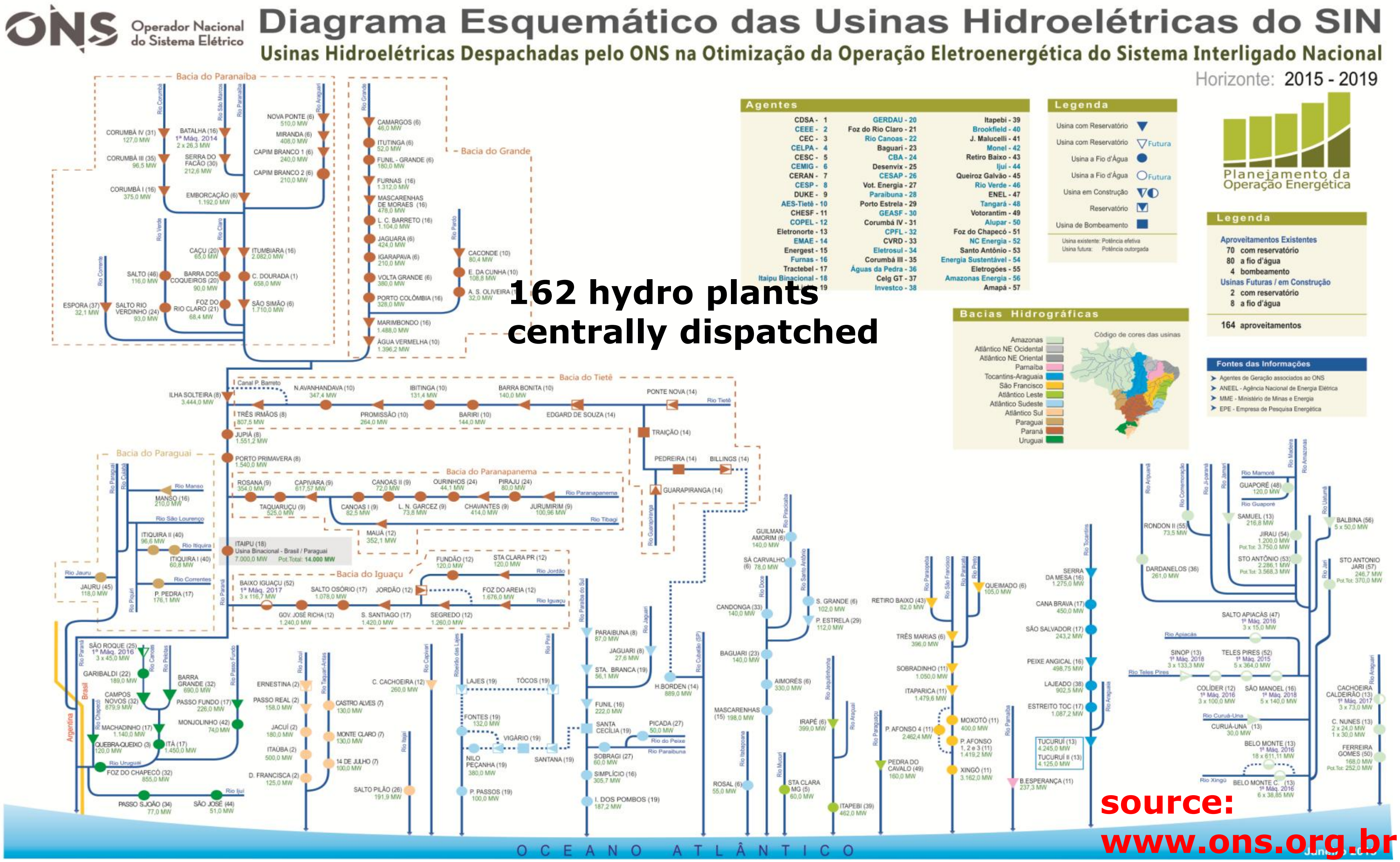




Coordinated operation is a VERY complex task!

BRAZILIAN INTERCONNECTED SYSTEM (SIN) – HYDRO PLANTS

Eletrobras
Cepel



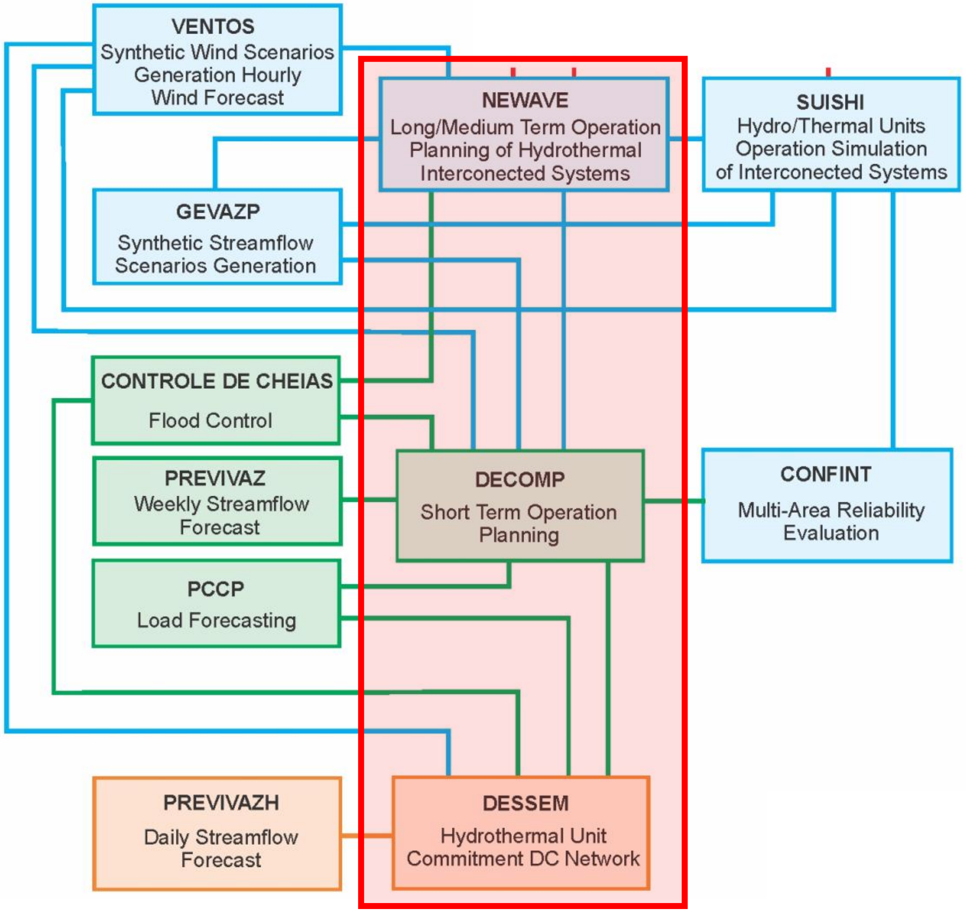
162 hydro plants centrally dispatched

source: www.ons.org.br

HYDROTHERMAL PLANNING FOR THE BRAZILIAN INTERCONNECTED SYSTEM

Eletrobras Cepel

LONG, MID, SHORT TERM HYDROTHERMAL POWER GENERATION PLANNING



Developed by CEPEL, collaborating with scientific comunity

Validated in working groups by ONS, CCEE, EPE, MME, ANEEL, as well as task forces with most power system utilities

Approved for official use by the regulatory agency

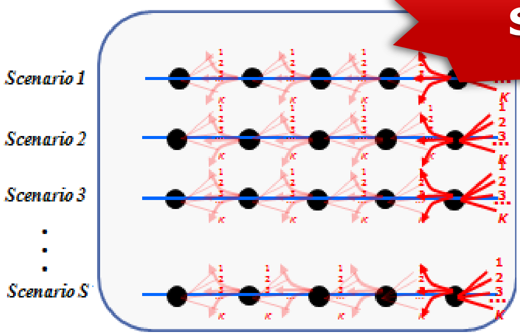
Used by:
- **ONS to dispatch the system**
- **CCEE to set market prices**

LONG, MID AND SHORT TERM GENERATION PLANNING

NEWAVE

SDDP

[Pereira,Pinto,91]
[Maceira,93]



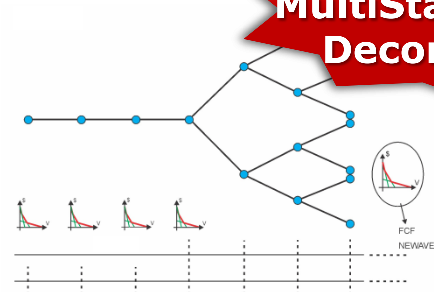
[Maceira,Duarte, Penna,Mor,Mel,08]

[Maceira,Penna, Diniz,Pinto,Melo, Vasconc.,Cruz,18]

DECOMP

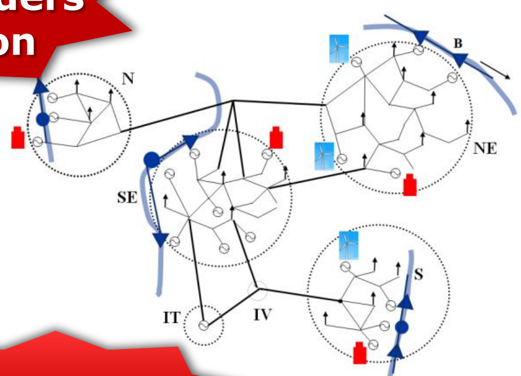
[Birge,85]

DDP
MultiStage Benders Decomposition



[Diniz,Costa,Maceira, Santos,Brandao,Cabral,18]

DESSEM



MILP

[Diniz,Souza, Maceira et al,02]

[Diniz, Santos, Saboia, Maceira,18]

Application of CVaR Risk Averse Mechanism

[Shapiro,Tekaya, Costa,Soares,12]

[Diniz, Tcheou, Maceira, 12]

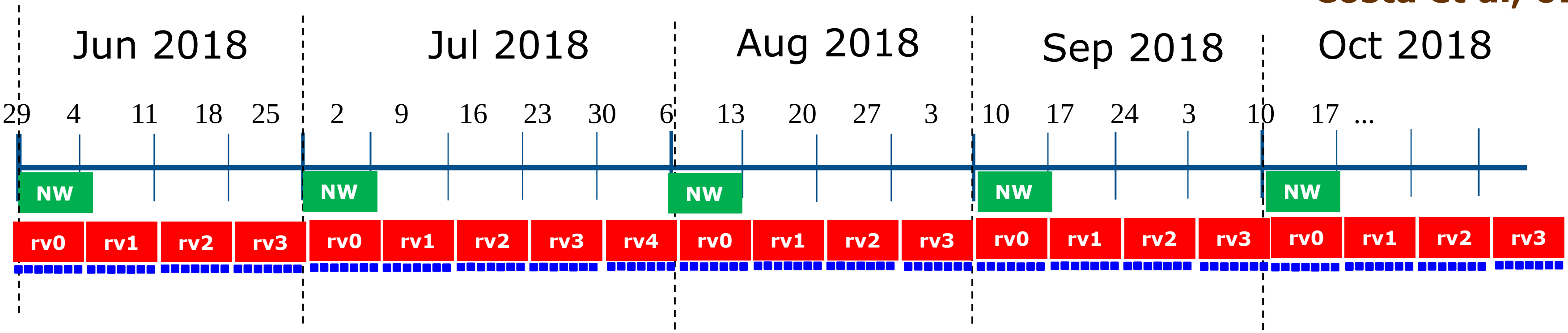
ROLLING HORIZON APPLICATION OF THE MODELS

	Application	Horizon	Time Step	Model	Scenario Tree	System Modeling	Solving Strategy
LONG	Monthly	10 years	Monthly	NEWAVE (since 2000)	Stochastic, sampling approach	Aggregate Reservoirs, tie-lines	SDDP
MID	Weekly	from 2 months to 1 year	Weekly/ Monthly	DECOMP (since 2002)	Stochastic, scenario tree	Individual Hydro Plants, tie-lines	MSBD
SHORT	Daily	2 weeks	Half-an-hour	DESSEM (2019-2020)	Determ.	unit commitment, DC power flow	MILP

NEWAVE → FCF → DECOMP → FCF, targets → DESSEM

ROLLING HORIZON APPLICATION

[Maceira, Terry, Costa et al, 02]



HYDROTHERMAL COORDINATION PROBLEM - OVERVIEW

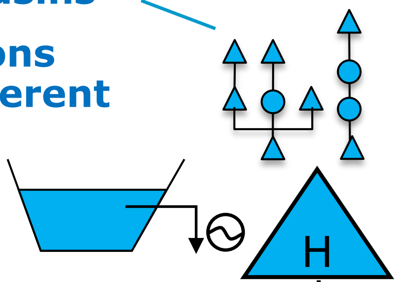
Eletrobras Cepel

The main objective is to minimize:

- Thermal Generation costs +
- Risk Measure (CVaR)

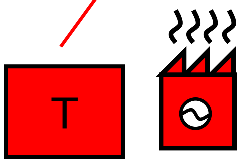
Subject to:

- Cascaded hydro plants in several river basins
- Pumping stations connecting different rivers
- Many hydro constraints



Hydro Plants

- thermal unit commitment constraints
- anticipated dispatch requirement of LNG units



Thermal Plants

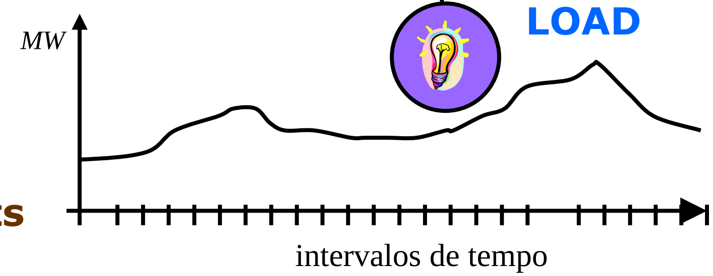
- Intermitent generation (new renewables)
- other fixed generations

Other sources

TRANSMISSION

- Interconnection limits among areas
- electrical losses in major interconnections
- line flow limits constraints (DC power flow)

LOAD



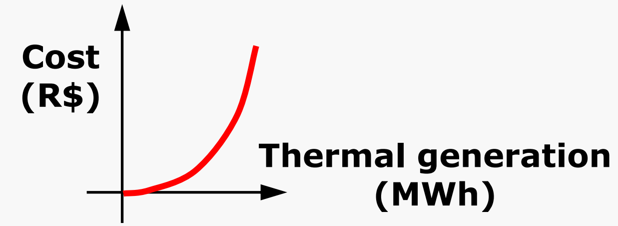
- MT/LT: Monthly/ weekly profiles in several load blocks, per system area
- ST: hourly load profiles, by bus

TARGET: to obtain an "optimal" Policy for planning purposes, to set the dispatch of hydro/thermal plants and to establish market prices

COST INFORMATION FOR DECISION MAKING

THERMAL PLANTS

- Exiplicit representation of thermal generation costs, as well as startup/shutdown costs

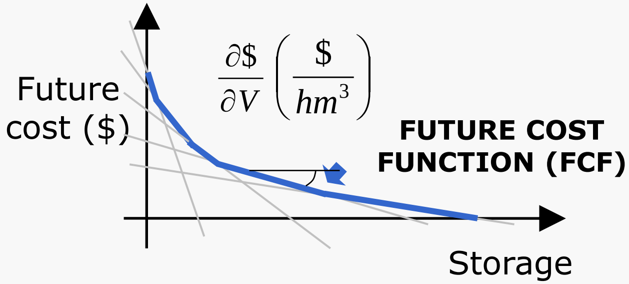


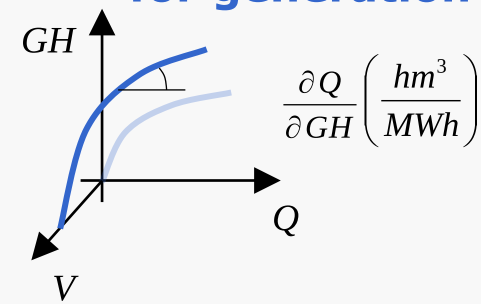
HYDRO PLANTS

- Combination of water values and plant efficiency yields hydro generation costs

Generation Costs = **Water Value** × **Water consumption for generation**

$$\left(\frac{\$}{MWh}\right)$$





NEW RENEWABLES (WIND, SOLAR...)

- Taking advantage of “free” generation as much as possible
- Energy storage to better manage intermittency (leads to future cost functions...)

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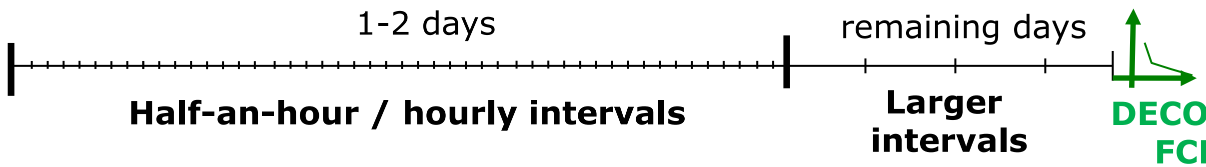
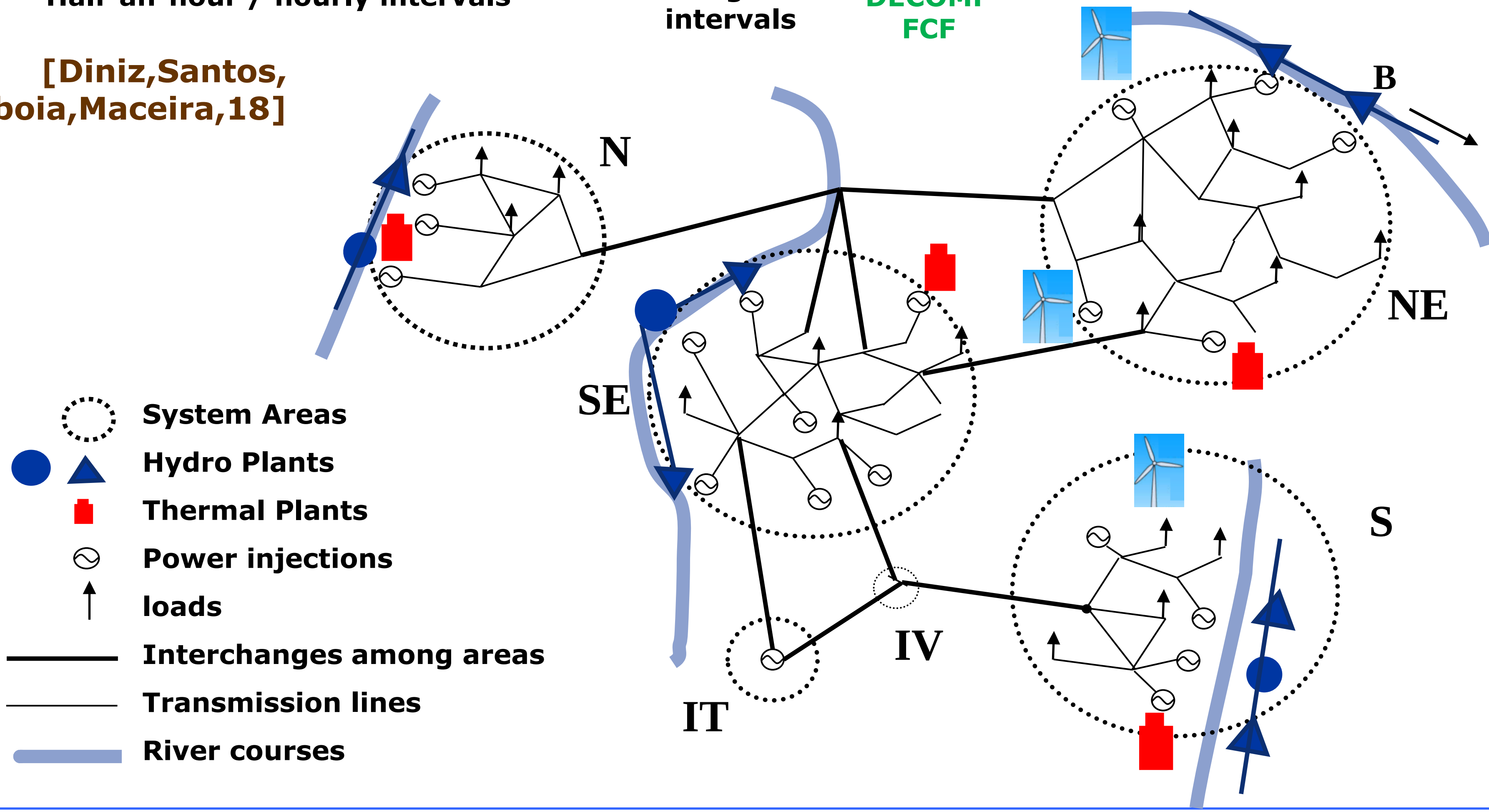
DETAILED REPRESENTATION OF THE ELECTRICAL NETWORK



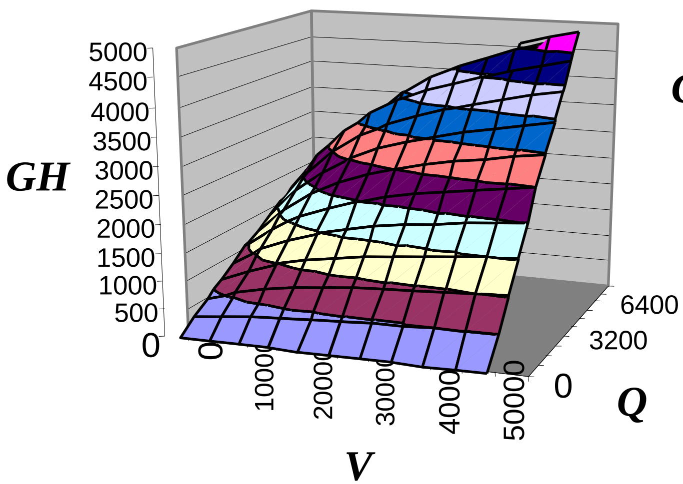
[Diniz,Santos, Saboia,Maceira,18]



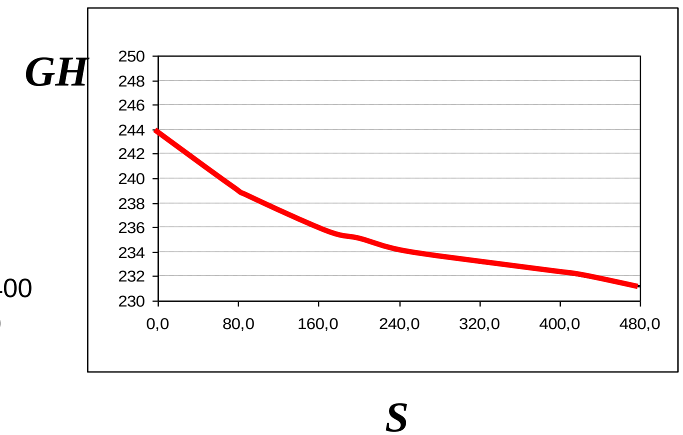
VARIATION OF EFFICIENCY WITH THE WATER HEAD

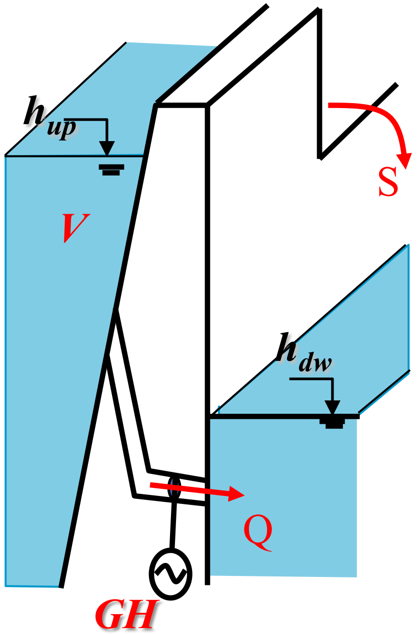
$$GH_i = 9.81 \times 10^{-3}\, \eta Q \left[h_{up}(V) - h_{dn}(Q+S) - h_{loss} \right]$$

Example of HPF as a function of *V* and *Q*



Example of HPF as a function of *S* (fixed values of *V* and *Q*)





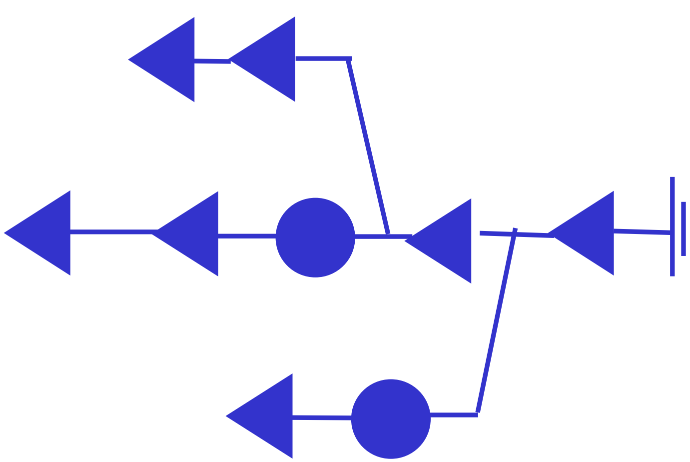
Four-dimensional piecewise linear model

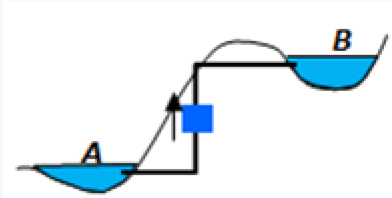
[Diniz,Maceira,08]

V, Q, S → **AHPF** → ***GH***

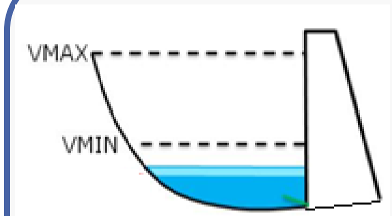
HYDRO CONSTRAINTS

HYDRO PLANTS IN CASCADE

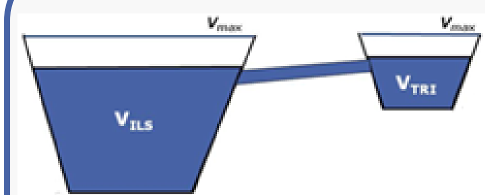




pumping stations

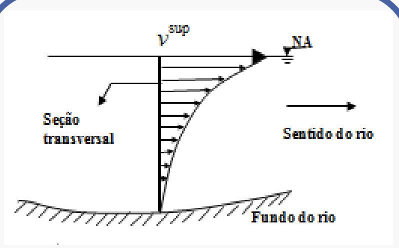


Filling of "dead volumes"

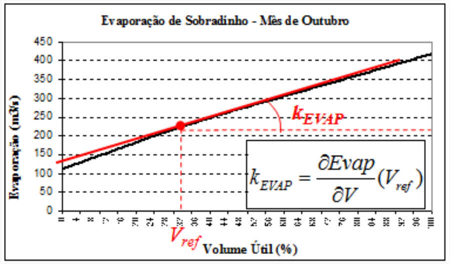


channels between reservoirs

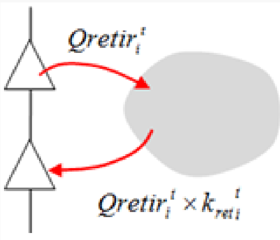
Minimum releases



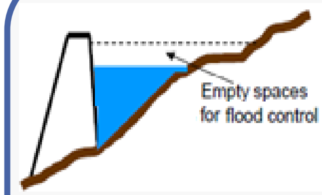
Modeling of river sections



Evaporation in reservoirs



Multiple uses of water

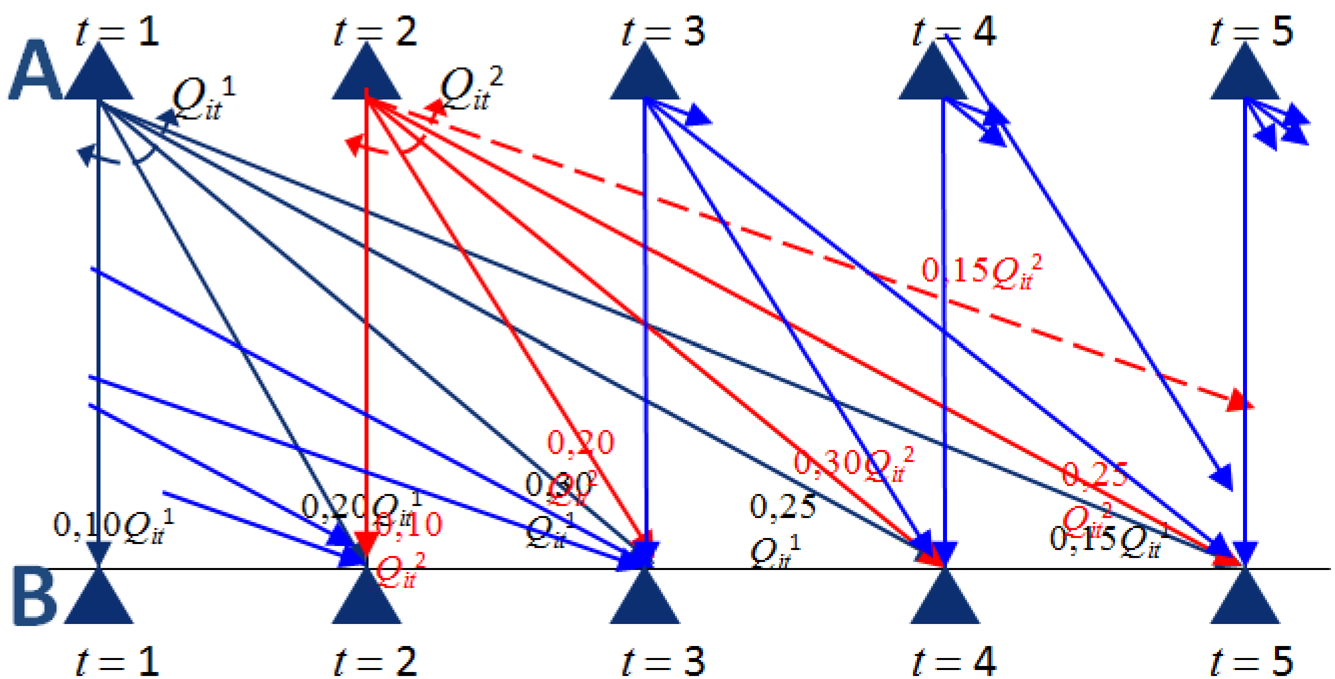


Flood control constraints

RIVER ROUTING

- Representation of water propagation curves along the river courses

[Diniz,Souza,14]



$$V_i^t + \left(Q_i^t + S_i^t\right) - \sum_{j \in M} \boxed{\sum_{k=0}^{\tau_{ij}^t} \kappa_{ij,k}^t} \left(Q_j^{t-\boxed{k}} + S_j^{t-\boxed{k}}\right) = V_i^{t-1} + I_i^t$$

NONCONVEX THERMAL UNIT COMMITMENT CONSTRAINTS (1/3)

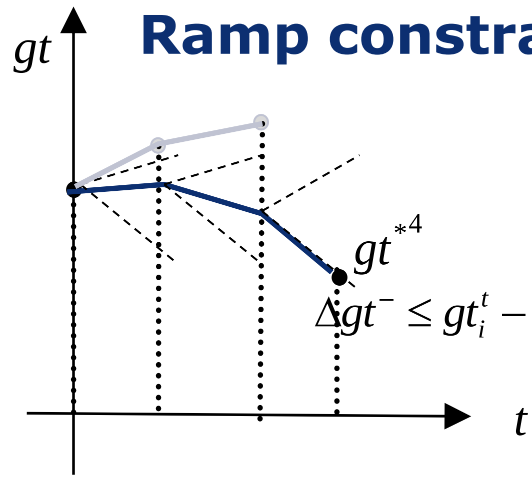
Minimum generation (once ON)

$$u_i^t \in \{0,1\} \qquad \underline{gt_i} \cdot u_i^t \le gt_i^t \le \overline{gt_i} \cdot u_i^t$$

Ramp constraints

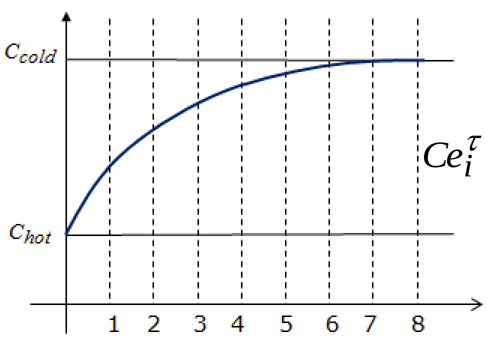
[Carrion, Arroyo,06]

[Saboia, Diniz,16]



$$\Delta gt^- \le gt_i^t - gt_i^{t-1} \le \Delta gt^+$$

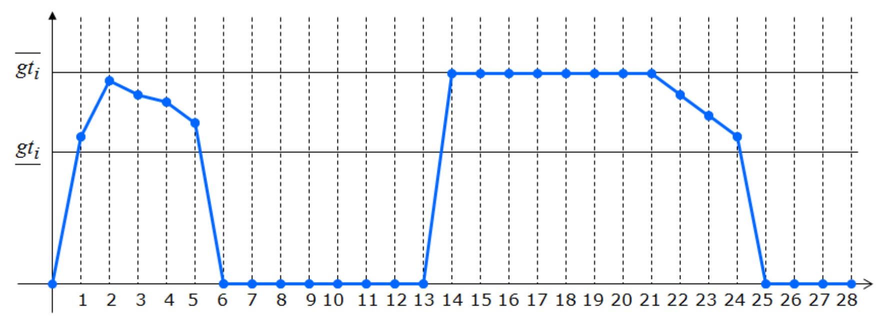
Startup/shutdown costs



$$Ce_i^{\tau}\left(u_i^t - \sum_{k=t-\tau}^{t} u_i^k\right) \le S_i^t$$

$$Cs_i\left(u_i^{t-1} - u_i^t\right) \le S_i^t$$

Minimum up/down times



$$\sum_{k=t}^{t+Ton_i-1} u_i^k \ge Ton_i \cdot (u_i^t - u_i^{t-1})$$

$$\sum_{k=t}^{t+Toff_i-1} (1-u_i^k) \ge Toff_i \cdot (u_i^{t-1} - u_i^t)$$

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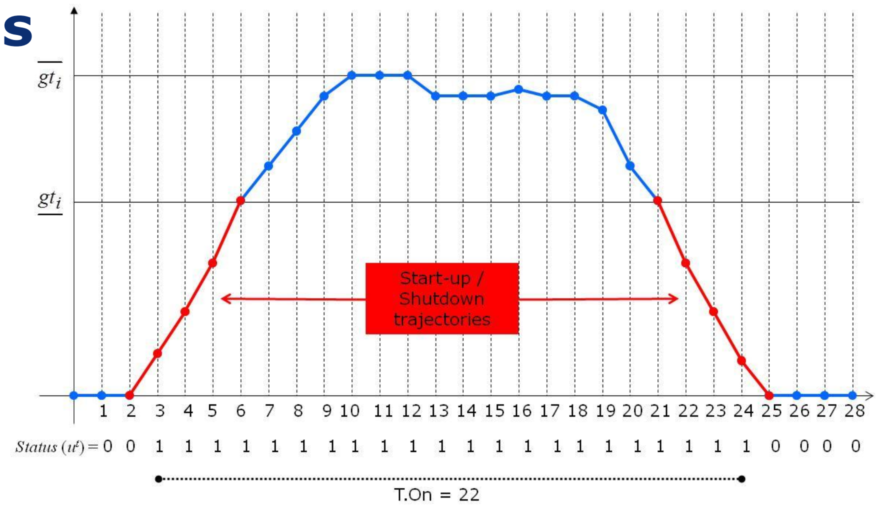
Start-up / Shutdown trajectories

$$GT_i^t \geq \underline{GT}_i \left(u_i^t - \sum_{k=1}^{NU_i} \hat{y}_i^{t-k+1} - \sum_{k=1}^{ND_i} \tilde{y}_i^{t+k-1} \right) + \sum_{k=1}^{NU_i} TrUp_i(k) \cdot \hat{y}_i^{t-k+1} + \sum_{k=1}^{ND_i} TrDn_i(ND_i - k + 1) \cdot \tilde{y}_i^{t+k-1}$$

$$GT_i^t \leq \overline{GT}_i \left(u_i^t - \sum_{k=1}^{NU_i} \hat{y}_i^{t-k+1} - \sum_{k=1}^{ND_i} \tilde{y}_i^{t+k-1} \right) + \sum_{k=1}^{NU_i} TrUp_i(k) \cdot \hat{y}_i^{t-k+1} + \sum_{k=1}^{ND_i} TrDn_i(ND_i - k + 1) \cdot \tilde{y}_i^{t+k-1}$$

[Arroyo, Conejo, 04]



Auxiliary variables:

$$\tilde{y}_i^t = \tilde{w}_i^t + \left(u_i^{t-1} - u_i^t \right)$$

$$\tilde{y}_i^t + \tilde{w}_i^t \leq 1$$

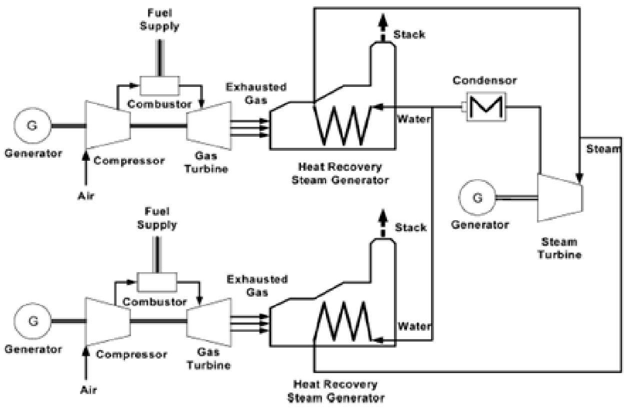
NU_i : length of startup trajectory

ND_i : length of shutdown trajectory

NONCONVEX THERMAL UNIT COMMITMENT CONSTRAINTS (3/3)

Operation of Combined-Cycle plants

- Application of a hybrid component/mode model
- Constraints can be individually enforced for the thermal units
- transition requirements between configurations can be included

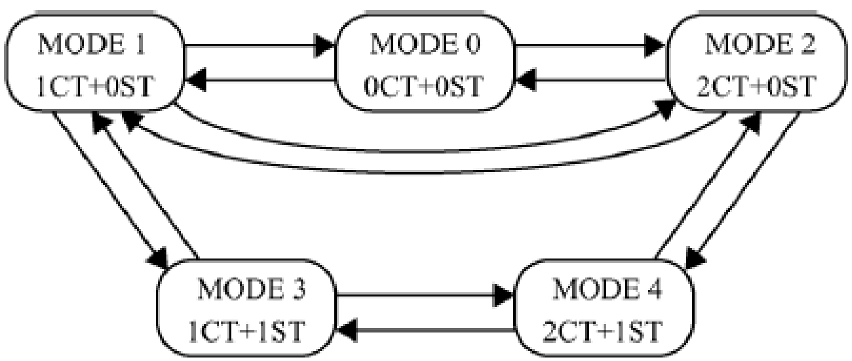


- Linking constraint between units status u_{ij}^t and configuration modes x_{ik}^t

[Liu,Shahidehpour, Li,Mahmoud,09]

[Morales-Espana, Correa-Posada, Ramod,16]

$$\begin{cases} \sum_{j \in NU_i} P_j u_{ij}^t = \sum_{k \in NC_i} N_k x_{ik}^t \\ \sum_{k \in NC_i} x_{ik}^t = 1 \\ u_{ij}^t, x_{ik}^t \in \{0,1\} \end{cases}$$



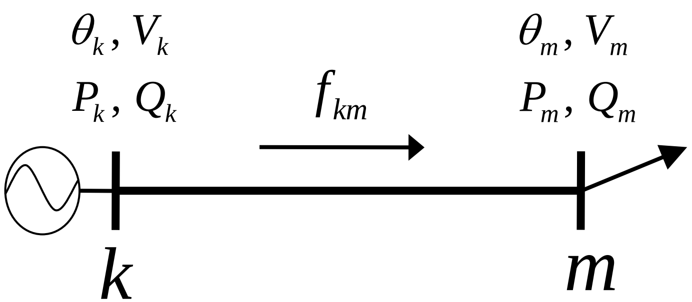
DC MODEL OF THE ELECTRICAL NETWORK

Line Flow limit constraints

$$\underline{f_{km}} \leq f_{km}^{t} = \frac{\theta_k^t - \theta_m^t}{x_{km}} \leq \overline{f_{km}}$$

- phase angles are a function of power injections / loads

$$\underbrace{\begin{bmatrix} g \end{bmatrix} - \begin{bmatrix} d \end{bmatrix}}_{gh,\ gt} = \begin{bmatrix} & B & \end{bmatrix} \begin{bmatrix} \theta \end{bmatrix}$$



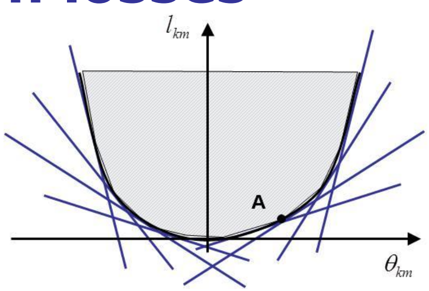
Ramp constraint on line flows

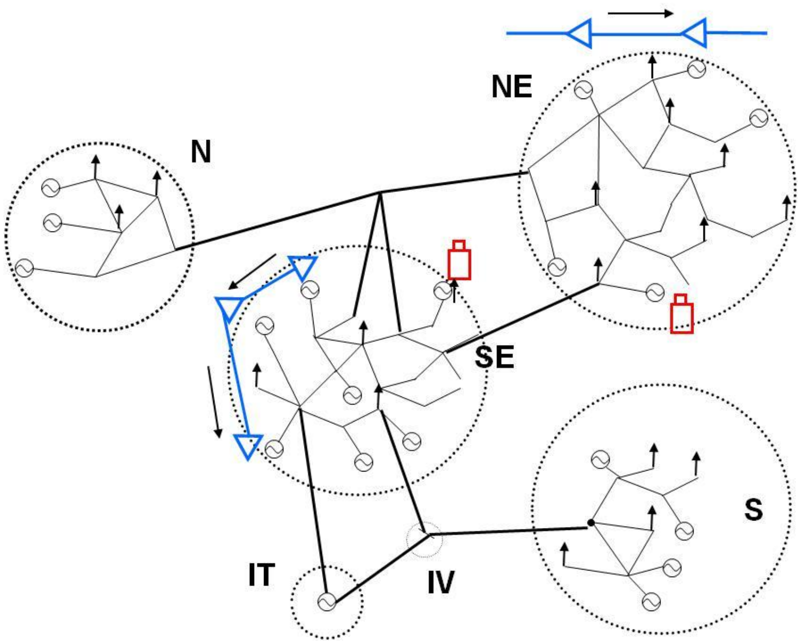
$$\left| f_{km}^{t} - f_{km}^{t-1} \right| \leq \overline{\Delta f_{km}}$$

Power transmission losses

- dynamic piecewise linear approximations

$$l_i \cong g_i \Delta\theta_i^{(k)^2}$$





- Line flow limits and approximations for losses are iteratively included

[Santos,Diniz,11]

ADDITIONAL SECURITY CONSTRAINTS

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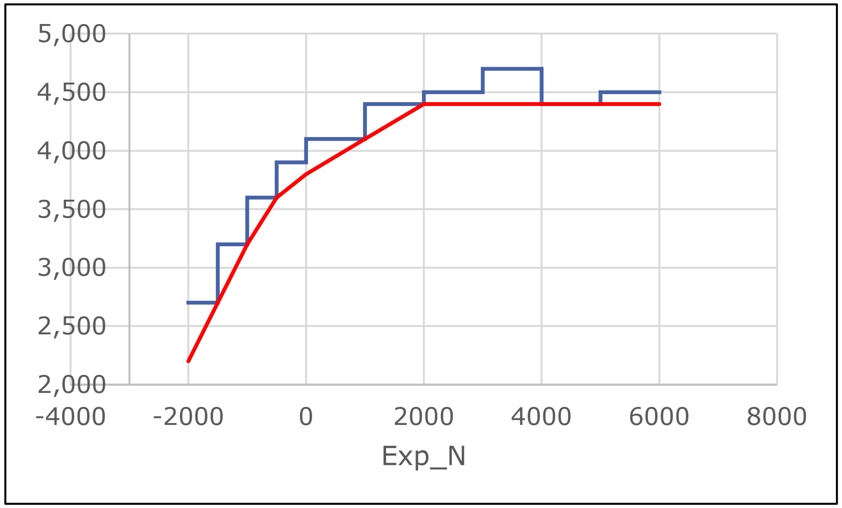
- constraints on the relation of flows in given lines of the system for security purposes

PIECEWISE LINEAR CONSTRAINTS



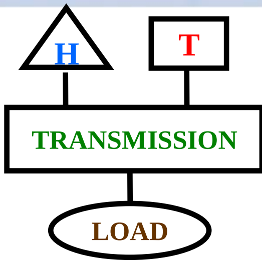
- some constraints are given by tables

HEURISTIC ITERATIVE APPROACH

LIMITES DE RNE (MW)						
	Carga NE < 10.500		10.500 ≤ Carga NE < 12.000		Carga NE ≥ 12.000	
Faixa de Recebimento / Exportação Norte (RN / Exp_N)	(F) = Somatório do fluxo na transformação 500/230 kV de Igaporã III, no sentido de 230 kV para o 500 kV e do fluxo na LT 230 kV Igaporã II / Bom Jesus da Lapa II, no sentido de Igaporã II para Bom Jesus da Lapa II.					
	0 < F ≤ 600	600 < F ≤ 1.050	0 < F ≤ 600	600 < F ≤ 1.050	0 < F ≤ 600	600 < F ≤ 1.050
Exp_N ≥ 5.000	Limite = 40% da carga NE	Limite = 40% da carga NE	4.400 (1)	4.300 (1)	4.400	4.300
4.000 ≤Exp_N< 5.000			4.300 (1)	4.300 (1)	4.300	4.300
3.000 ≤Exp_N< 4.000		4.200 (1)	4.200 (1)	4.200 (1)	4.200	4.200
2.000 ≤Exp_N< 3.000		4.100 (1)	4.100	4.100	4.100	4.100
1.000 ≤Exp_N< 2.000		3.900 (1)	4.000	3.900	4.000	3.900
0 ≤Exp_N< 1.000	4.100 (1)	3.600 (1)	4.000	3.700	4.000	3.500
0 < RN ≤ 500	3.900 (1)	3.300 (1)	4.000	3.500	4.000	3.500
500 < RN ≤ 1.000	3.600 (1)	3.000 (1)	3.800	3.200	4.000	3.300
1.000 < RN ≤ 1.500	3.200 (1)	2.700 (1)	3.400	2.900	3.600	2.900

OVERALL PROBLEM FORMULATION

MIXED INTEGER (PIECEWISE) LINEAR PROGRAMMING



$$\min \sum_{t=1}^{T}\sum_{i=1}^{NUT} c_i(gt_i^t) + S_i^t + \alpha^T\left(V^T\right)$$

s.a.

E

Demand

$$\sum_{j\in\Phi_i} gt_j^t + \sum_{j\in\Psi_i} gh_j^t + \sum_{j\in\Omega_i}\left(Int_{j\to i}^t - Int_{i\to j}^t\right) = D_i^t \qquad i=1,\ldots,NS,\ t=1,\ldots,T,$$

Electrical network

$$\sum_{i=1}^{NB}\kappa_{i,l}(g_i-d_i)\le \overline{f}_l \ ;\ p_i-\sum_{i=1}^{NB}\kappa_{i,l}(g_i-d_i)\le rhs \qquad i,j=1,\ldots,NL,\ t=1,\ldots,T$$

H

Water balance

$$V_i^t = V_i^{t-1} + I_i^t - (Q_i^t + S_i^t) + \sum_{j\in M_i}(Q_j^t + S_j^t)$$

AHPF

$$gh_i^t = FPH(V_i^t, Q_i^t, S_i^t)$$

Operative constraints

$$\underline{V}_i^t \le V_i^t \le \overline{V}_i^t,\quad \underline{Q}_i^t \le Q_i^t \le \overline{Q}_i^t,\quad \underline{gh}_i^t \le gh_i^t \le \overline{gh}_i^t, \qquad i=1,\ldots,NH,\ t=1,\ldots,T,$$

T

Termal constraints

$$\underline{gt}_i\cdot u_i^t \le gt_i^t \le \overline{gt}_i\cdot u_i^t$$

$$Ce_i^\tau\left(u_i^t - \sum_{k=t-\tau}^{t} u_i^k\right)\le S_i^t \qquad Cs_i\left(u_i^{t-1}-u_i^t\right)\le S_i^t$$

Unit Commitment

$$\sum_{k=t}^{t+Ton_i-1} u_i^k \ge Ton_i\cdot(u_i^t - u_i^{t-1})$$

$$\sum_{k=t}^{t+Toff_i-1}(1-u_i^k) \ge Toff_i\cdot(u_i^{t-1} - u_i^t)$$

$$\underline{GT}_i\left(u_i^t - \sum_{k=1}^{NU_i}\hat{y}_i^{t-k+1} - \sum_{k=1}^{ND_i}\tilde{y}_i^{t+k-1}\right) + \sum_{k=1}^{NU_i} TrUp_i(k)\cdot\hat{y}_i^{t-k+1} + \sum_{k=1}^{ND_i} TrDn_i(ND_i-k+1)\cdot\tilde{y}_i^{t+k-1} \le GT_i^t \le \overline{GT}_i\left(u_i^t - \sum_{k=1}^{NU_i}\hat{y}_i^{t-k+1} - \sum_{k=1}^{ND_i}\tilde{y}_i^{t+k-1}\right) + \sum_{k=1}^{NU_i} TrUp_i(k)\cdot\hat{y}_i^{t-k+1} + \sum_{k=1}^{ND_i} TrDn_i(ND_i-k+1)\cdot\tilde{y}_i^{t+k-1}$$

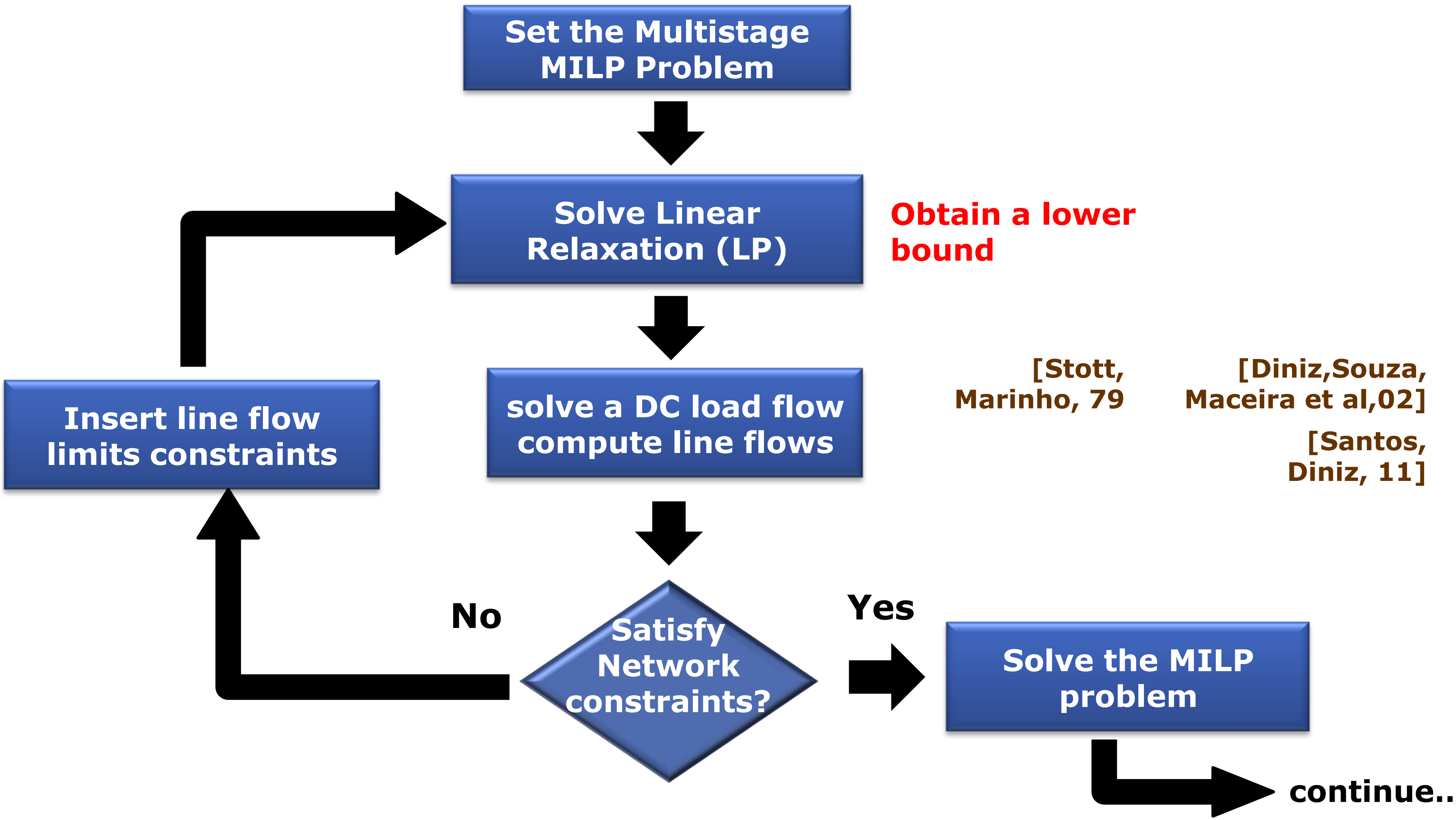
$$u_i^t\in\{0,1\} \qquad \tilde{y}_i^t = \tilde{w}_i^t + \left(u_i^{t-1}-u_i^t\right) \qquad \tilde{y}_i^t + \tilde{w}_i^t \le 1$$

$$i=1,\ldots,NUT,\ t=1,\ldots,T,$$

+ MANY more constrainsts...

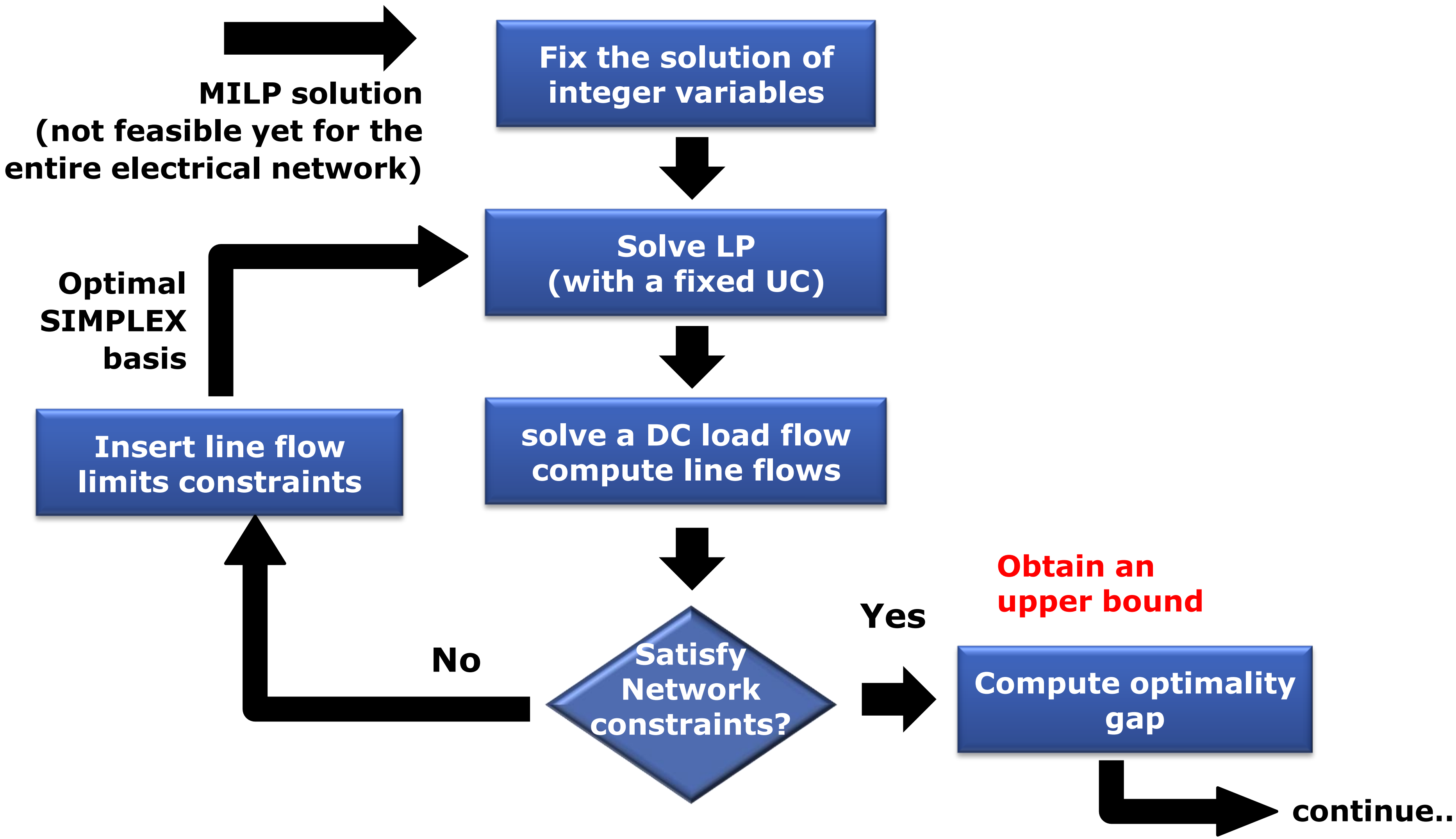
Solving Strategy: MILP (1/3)

ITERATIVE LP APPROACH TO FIND MAJOR / POTENTIAL BINDING CONSTRAINTS IN THE ELECTRICAL NETWORK

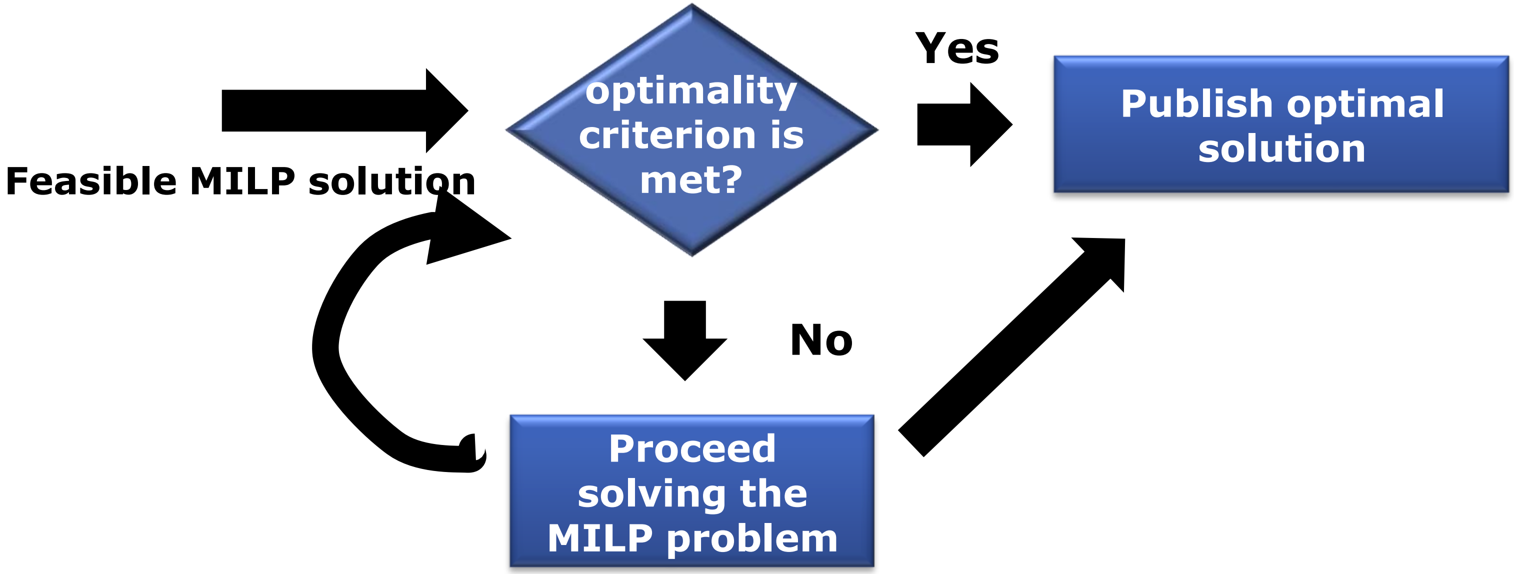


Solving Strategy: MILP (2/3)

ITERATIVE LP WITH FIXED UC TO OBTAIN A GOOD (?) FEASIBLE SOLUTION



FINDING AN OPTIMAL SOLUTION WITH THE DESIRED ACCURACY



DETERMINATION OF MARKET PRICES

Obtain nodal prices for all buses of the system

"Optimal "solution has been reached → Fix commitent status of the units → Solve a continuous hydrothermal scheduling problem → Obtain multipliers for system area and line flow limits constraints

System are price as weighted average in all buses

Multipliers of demand balance in each area

$$\sum_{\substack{i=1 \\ i\in k}}^{NH,NT} g_i \pm \sum_{j\in\Omega_k} Int_{j\rightarrow i} = \sum_{i\in Area\ k} d_i \ , \ k = 1,\ldots NS \longleftarrow \lambda_k^d$$

Multipliers of line flow limits constraints

$$\sum_{i=1}^{NB} \kappa_{il} g_i \leq f_{l\max} + \sum_{i=1}^{NB} \kappa_{il} d_i \ , \ \ l = 1,\ldots NL_{adic}, \longleftarrow \lambda_l^f$$

Nodal price:

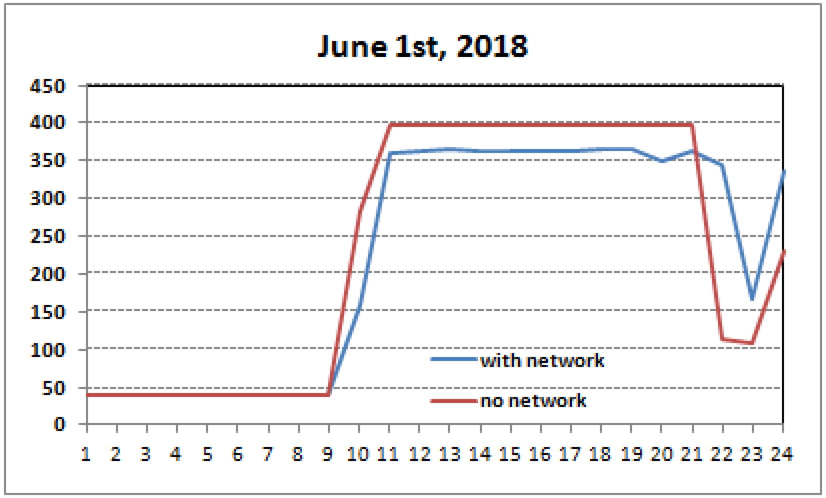
$$CMB_i = \lambda_{a(i)}^d + \sum_{l=1}^{NL_{adic}} \kappa_{il} \ \lambda_l^f$$

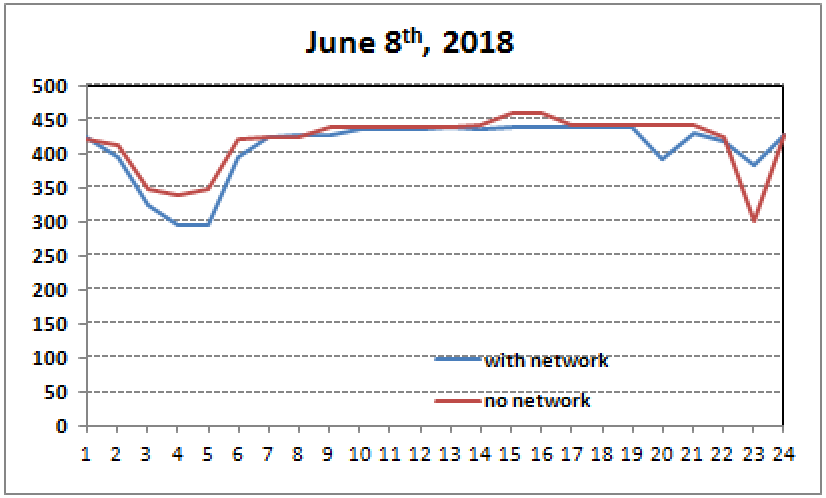
System Area price:

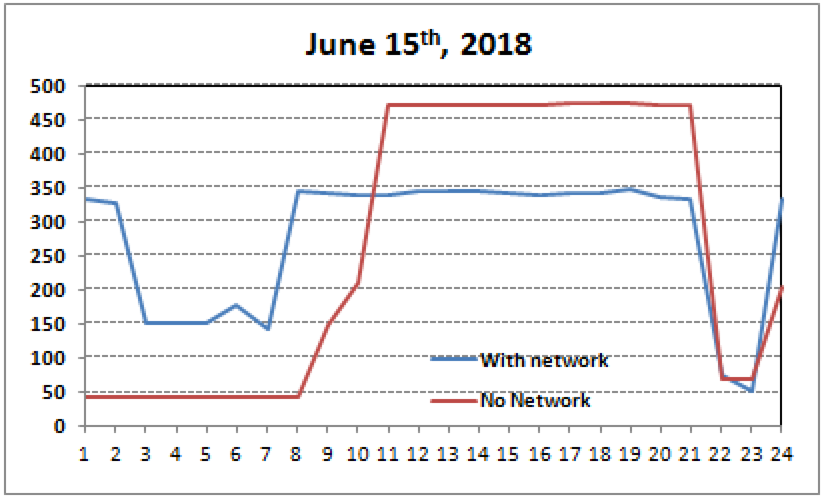
$$\boxed{CMO_k = \frac{\sum_{\substack{i=1 \\ i\in k}}^{NB} CMB_i d_i}{\sum_{\substack{i=1 \\ i\in k}}^{NB} d_i}}$$

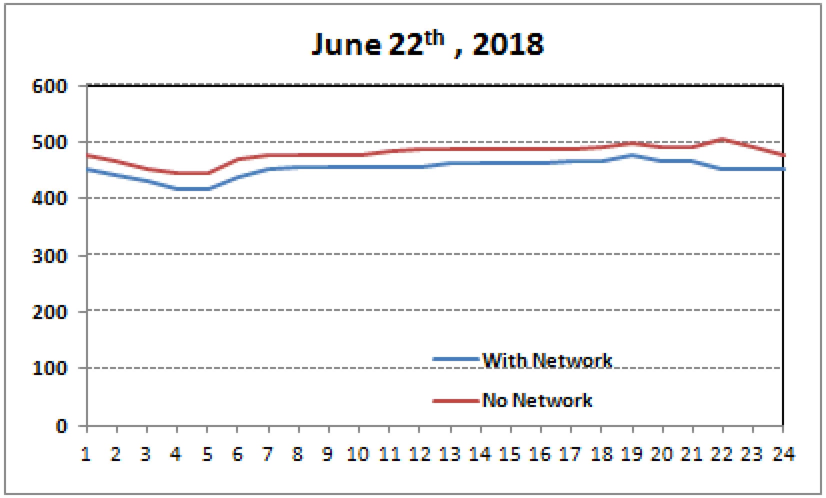
HOURLY PRICES RESULTS "shadow" operation

SYSTEM MARGINAL PRICES - NORTHEAST REGION (NE)









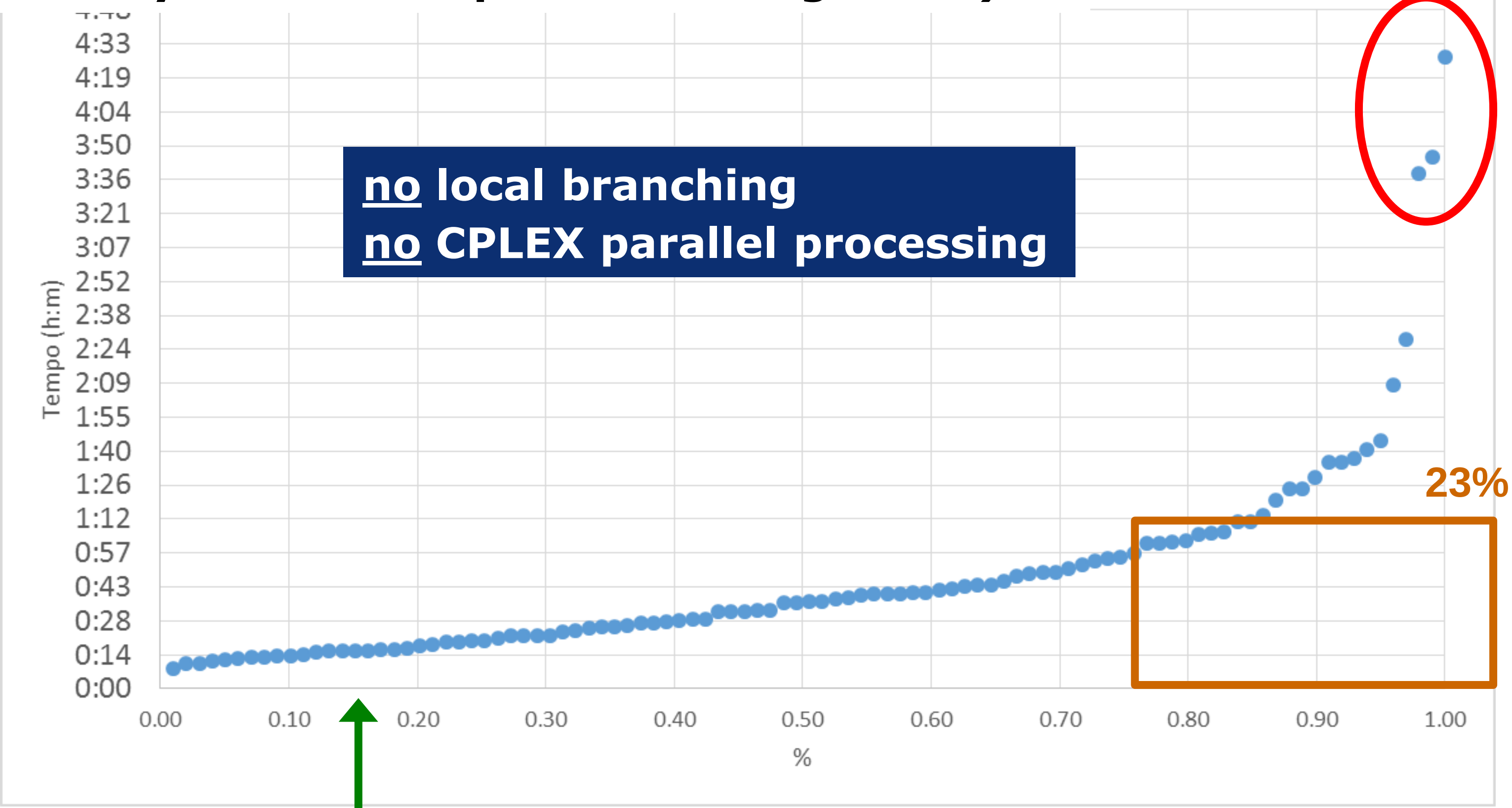
source: www.ccee.org.br

PERFORMANCE RESULTS
"shadow" operation

Eletrobras Cepel

CUMULATIVE DISTRIBUTION OF CPU TIMES

(all daily runs from April 16th to August 1st)



<u>no</u> local branching
<u>no</u> CPLEX parallel processing

4% of the cases:
\> 2h

23% of the cases:
\> 1h

25% of the cases:
< 20min

source: www.ons.org.br

#Hydro Plants:	**158**
#Thermal Plants:	**109**
#Network Buses:	**6,450**
#Transmission Lines:	**8,850**

FURTHER DEVELOPMENTS: REDUCTION OF CPU TIMES

- Use of tighter/more compact unit commitment formulations **[Ostrowsku, Anjos,Vanneli, 13]** **[Dam, Kucuk, Rajan, Atam, 13]** **[Morales-Espana, Latorre, Ramos, 13]**

- Taking into account optimal basis informationwhile adding new constraints to the problem **<u>in a MILP setting</u>**

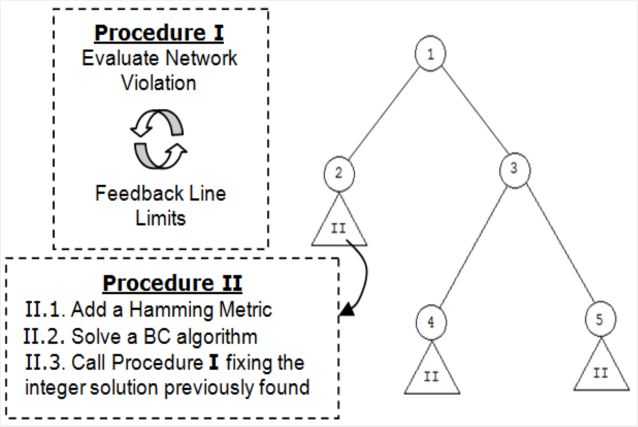
- Alternative (better) interaction between MILP and LP solving procedures
  - ✓ Application of local branching

Hamming Metric

[Fischetti, Lodi,03]

[Saboia, Diniz,16]

$$\Delta(u,\bar{u}) = \sum_{\{v:(\bar{u})^v=1\}} [1-(u)^v] + \sum_{\{v:(\bar{u})^v=0\}} (u)^v$$



PRACTICAL ASPECTS

FEASIBILITY OF THE SOLUTION

- operation constraints are modeled with slack variables to allow violation (at high penalty costs), since the inclusion of all constraints by the ISO usually leads to an infeasible problem

- however, optimality gap for the integer solution (1%) is beyond the accuracy for the penalty costs for violations of some constraints

Inclusion of an additional constraint to force all slack variables to zero in order to check the problem feasibility

REPRODUTIBILITY OF THE RESULTS

- parallel processing feature of CPLEX solver has beene enabled to ensure the same results are obtained in different computers

SUMMARY
Evolution of "hourly price" process

Eletrobras Cepel

- 1999 – 2017: Ongoing evolution of the DESSEM model
- **Sept 2017 – April 2018:** validation of the features of the model available at that time
  - ✓ Shadow operation starting on April 16^{th} (1st phase)
- **April 2018 – December 2018** - Development and validation of new features requested by the Brazilian ISO
  - ✓ Additional security constraints
  - ✓ Operation of combined-cycle plants
- **2019:** Second phase of the shadow operation (all features)
  - ✓ validation of the process by the task force (ONS, CCEE, utilities)
- **The method to obtain hourly prices is still under discussion**
- **2020:** oficial use for day ahead dispatch and hourly prices

REFERENCES

[Arroyo, Conejo, 04] Arroyo, J.M., Conejo, A.J., "Modeling of start-up and shut-down power trajectories of thermal units", IEEE Transactions on Power Systems, v.19, n. 3, pp 1562-1568, Aug. 2004.

[Birge,85] J.R. Birge, "Decomposition and partitioning methods for multistage stochastic linear programs", Operations Research, v.33, n.5, pp. 989-1007, 1985.

[Birge, Louveaux,97] J. R. Birge, F. Louveaux, "Introduction to stochastic programming", Springer series in OR, 1997.

[Carrion, Arroyo,06] M. Carrion, J. M. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem", IEEE Transactions on Power Systems, v. 21, n. 3, pp. 1371-1378, Aug. 2006.

[Dam, Kucuk, Rajan, Atam, 13] P. Damci-Kurt, S. Kucukyavuz, D. Rajan, and A. Atamturk, A Polyhedral Study of Ramping in Unit Committment, Univ. of California-Berkeley, Res. Rep. BCOL.13.02 IEOR, Oct. 2013 Available: http://ieor.berkeley.edu/atamturk/pubs/ramping.pdf

[Diniz,Costa, Maceira, Santos, Brandao,Cabral,18] A. L. Diniz, F. S. Costa, M. E. P. Maceira, T. N. Santos, L. C. Brandão, R. N. Cabral, "Short/Mid-Term Hydrothermal Dispatch and Spot Pricing for Large-Scale Systems - the Case of Brazil", 20th Power Systems Computation Conf., Ireland, June 2018.

[Diniz, Maceira,08] A.L. Diniz, M.E.P. Maceira, , "A four-dimensional model of hydro generation for the short-term hydrothermal dispatch problem considering head and spillage effects", IEEE Trans. Power Syst., v. 23, n.3, pp. 1298-1308,2008.

[Diniz, Santos, Saboia, Maceira,18] A. L. Diniz, T.N.Santos, C.H. Saboia, M.E.P. Maceira,"Network constrained hydrothermal unit commitment problem for hourly dispatch and price setting in Brazil: the DESSEM model', Accepted for presentation in the 6th Int. Workshop on Hydro Scheduling in Competitive Electricity Markets, Norway,2018.

REFERENCES

[Diniz,Sousa, Maceira et al,02] A. L. Diniz, L. C. F. Sousa, M. E. P. Maceira, S. P. Romero, F. S. Costa, C. A. Sagastizabal, A. Belloni, "Estratégia de representação DC da rede elétrica no modelo de despacho da operação energética – DESSEM", VIII SEPOPE,2002.

[Diniz, Souza,14] A. L. Diniz, T. M. Souza, "Short-Term Hydrothermal Dispatch With River-Level and Routing Constraints", IEEE Trans. Power Systems, v.29, n.5, p. 2427–2435, 2014.

[Diniz, Tcheou, Maceira,12] A. L. Diniz, M. P. Tcheou, M. E. P. Maceira, "Uma abordagem direta para consideração do CVAR no problema de planejamento da operação hidrotérmica" XII SEPOPE - Symposium of Specialists in Electric Operational and Expansion Planning,2012

[Fischetti, Lodi, 03] M. Fischetti, m".Lodi, "Local Branching", Mathematical Programming Series B, v.98, pp. 23-47, 2003

[Kall, Mayer,10] P. Kall, J. Mayer, "Stochastic linear programming: models, theory and computation", John Wiley & Sons, 2ed,2010

[Liu,Shahidehpour, Li,Mahmoud,09] C. Liu, M. Shahidehpour, Z. Li, M. Fotuhi-Firuzabad, "Component and Mode Models for the short term scheduling of Combined Cycle Units" IEEE Trans. Power Syst., vol. 24, no. 2, pp. 976-990, May 2009.

[Maceira,93] M.E.P Maceira, "Programação Dinâmica Dual Estocástica Aplicada ao Planejamento da Operação Energética de Sistemas Hidrotérmicos com Representação do Processo Estocástico de Afluências por Modelos Auto-Regressivos Periódicos", Rel. Técnico CEPEL 237/93, 1993.

[Maceira,Duarte, Penna,Mor, Melo,08] M.E.P. Maceira, V.S. Duarte, D.D.J. Penna, L.A.M. Moraes, A.C.G. Melo, "Ten years of application of stochastic dual dynamic Programming in official and agent studies in Brazil – Description of the NEWAVE program", 16th PSCC Conf. , Glasgow, July 2008.

REFERENCES

[Maceira,Penna, Diniz,Pinto,Melo, Vasconc.,Cruz,18] M.E.P. Maceira, D.D.J. Penna, A.L. Diniz, R.J. Pinto, A.C.G. Melo, C.V. Vasconcellos, C.B. Cruz, "Twenty Years of Application of Stochastic Dual Dynamic Programming in Official and Agent Studies in Brazil – Main Features and Improvements on the NEWAVE Model", Power Syst. Computation Conference (PSCC), Dublin, June 2018.

[Maceira, Terry, Costa et al, 02] M.E.P. Maceira, L.A. Terry, F.S. Costa, J. M. Damazio, A C. G. Melo, "Chain of optimization models for setting the energy dispatch and spot price in the Brazilian system", Proceedings of the Power System Computation Conference – PSCC,2002.

[Morales-Espana, Latorre, Ramos, 13] G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation of start-up and shut-down ramping in unit commitment," IEEE Trans. Power Syst., vol. 28, no. 2, pp. 1288–1296, May 2013.

[Morales-Espana, Correa-Posada, Ramod,16] G. Morales-Espana, C,M. Correa-Posada and A. Ramos, "Tight and compact MILP formulation of Configuration-Based Combined-Cycle Units," IEEE Trans. Power Syst., vol. 31, no. 2, pp. 1350–1359, March 2016.

[Ostrowsku, Anjos,Vanneli, 13] J. Ostrowski, M. Anjos, and A. Vannelli, "Tight mixed integer linear programming formulations for the unit commitment problem," IEEE Trans. Power Syst., vol. 27, no. 1, pp. 39–46, Feb. 2012.

[Pereira, Pinto,91] M. V. F. Pereira, L. M. V. G. Pinto, "Multi-stage stochastic optimization applied to energy planning", Mathematical Programming, v. 52, n.1-3, pp. 359-375, May 1991.

[Saboia, Lucena,11] C. H. Saboia, A. Lucena, "A column generation approach for solving very large scale instances of the brazilian long term power expansion planning model, 17th PSCC - Power Syst. Comp. Conf., Stockholm, Sweden, Aug. 2011.

[Saboia, Diniz,16] C. H. M. de Saboia, A. L. Diniz, "A local branching approach for network-constrained thermal unit commitment problem under uncertainty", 19th Power Systems Computation Conference (PSCC), Genoa, Italy, Jun. 2016.

REFERENCES

[Santos, Diniz, 11] T. N. Santos, A. L. Diniz, "A Dynamic Piecewise Linear Model for DC Transmission Losses in Optimal Scheduling Problems", IEEE Transactions on Power Systems, v.26, n.2, pp. 508-519, May 2011.

[Shapiro,Tekaya, Costa,Soares,12] A. Shapiro, W. Tekaya, J.P. Costa, M.P. Soares, "Risk neutral and risk averse Stochastic Dual Dynamic Programming method", European journal of operational research, v. 224, n.2, pp. 0375-0391, Jan. 2013

[Stott, Marinho, 79 B. Stott, J. L. Marinho, "Linear programming for power-system network security applications", IEEE Trans. Power Apparatus and Systems, v. 98, n.3, pp. 837-848, 1979.

TUSEN TAKK!

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