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Optimal Long-Term Generation-Transmission Planning in the Context of Multiple TSOs

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Contents

Introduction

The EU has set itself a long-term goal of reducing greenhouse gas emissions by 80-95% when compared to 1990 levels by 2050 [1]:

- DG and Smart Grid
- Renewables
- **Cross-border Lines**

  Economical issues:

  - ❑ TSOs are reluctant to act in a cooperative solution.
  - ❑ TSO transmission investment should be coordinated with GENCOs generation investments.

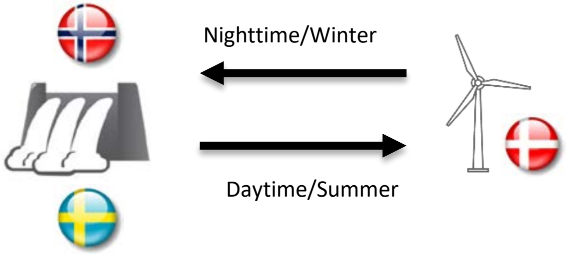
[1] 2050 Energy Strategy, European Commission.

Introduction

Motivation

Emerging Need for Investments in Electric Power System:

- increase of demand (South America's countries, South Africa, China, India)
- cross-border market integration,
- RES integration
- security of supply improvement

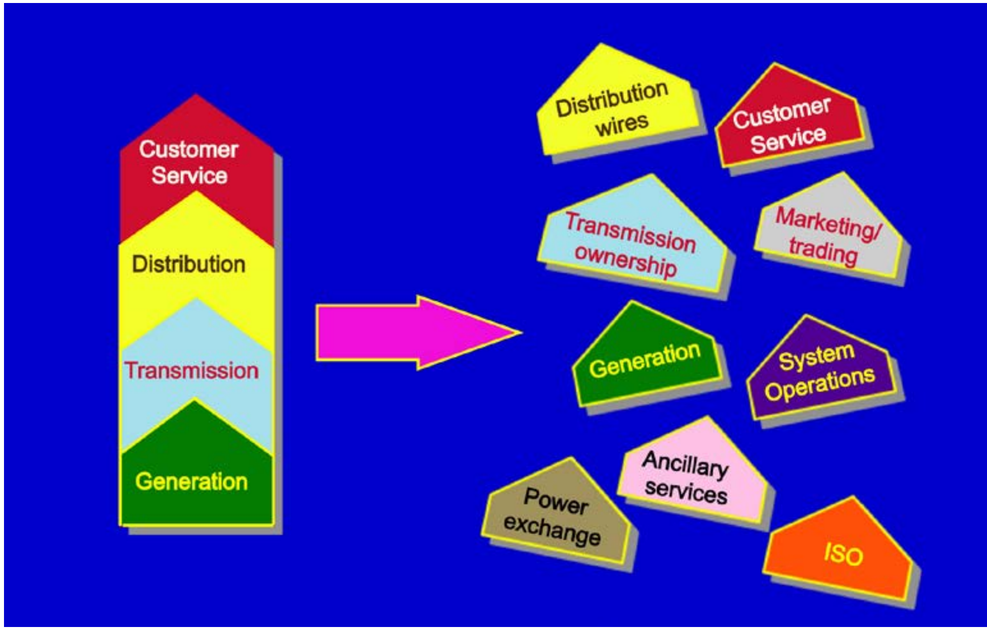


Introduction

Motivation

From Vertically Integrated Utilities to the Multi-player and Complex Power Systems

- Emerging technologies
- Belief in market mechanisms



Introduction

Questiones

- How is the option of cooperative TSOs as compared to non-cooperative TSOs?
- How transmission and generation planning are coordinated in a deregulated environment?
- What mechanism can improve the planning result in a deregulated power system with multiple regions?

Toward the Answers

- ✓ Evaluate the differences between the two **cooperative and non-cooperative** approaches (horizontal coordination).
- ✓ Comparing different market designs for **coordination** of transmission and generation planning (vertical coordination).
- ✓ **Solving an efficient** transmission-generation planning model in the context of multi-TSO multi-GENCO (computational difficulties and mechanism design).

Introduction

Objectives

- Analyzing the transmission and generation investment in a multi-player environment.
- Evaluating the result in each study as compared to the ideal result
- Analyzing different ways of changing the situation in order to become closer to the ideal situation.

• Improving the semantics

Assumptions:

- Network constraints modelled using DC power flow
  - Power balance constraint
  - Generation capacity limits
  - Transmission capacity limits
- In the dispatch level, the operation cost of the whole system is minimized.
- Nodal prices are derived from the dispatch level (endogenously).
- Expansion planning is static and for a certain period in the future.
- Transmission system is planned by an entity minimizing the social cost of its region (TSO)
- Generation units are planned by profit maximizing companies (Gencos)

Introduction

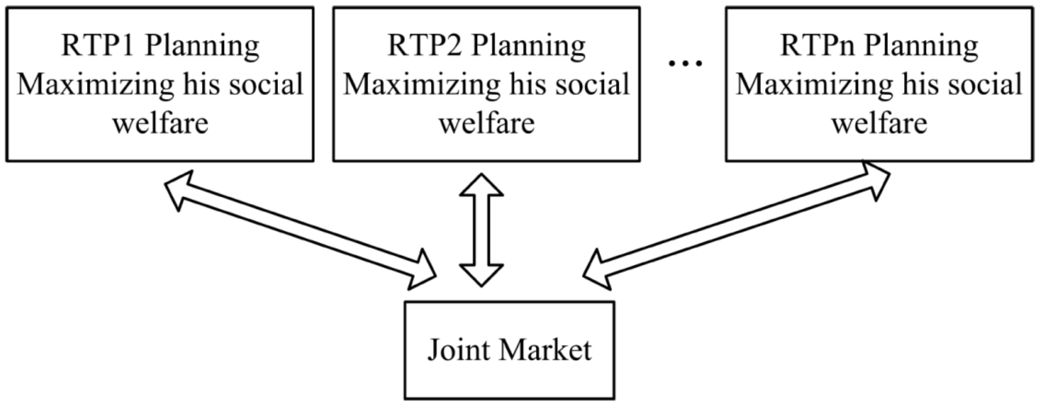
Definitions

- **Coordination** is the task of designing/modifying the situation in order to become closer to the desired result while being fair/just. This is done by a higher body (ACER in Europe and FERC in US).
- **Horizontal coordination** relates to transmission investment of neighbouring regions/countries.
- **Vertical coordination** relates to generation and transmission investment of a network.
- **Centralized planning (benchmark)** is the theoretical planning scheme by minimizing the social cost of the whole system .

Horizontal coordination

- **Issue:** The decision of one entity minimizing the total social cost of the whole inter-connected system *cause looser and winners*.
- Example:
  - "cap and floor" contracts of transmission investment provides Ofgem with a mechanism to reflect the cost that the project imposes on the rest of the network
- **Contribution:** Modelling of non-cooperative transmission planning of TSOs considering a simple mechanism for coordination.

Horizontal coordination
Method



Simultaneous-move Game

An optimisation problem:

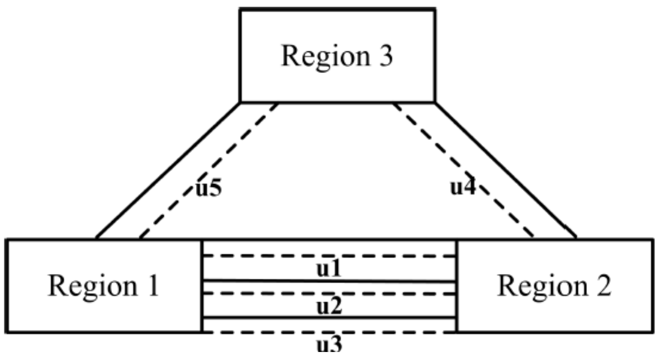
- Equivalent Karush-Kuhn-Tucker (KKT) optimality condition
- Linearisation techniques

Multiple Nash equilibria:

- Wost Nash equilibrium

Y. Tohidi and M. R. Hesamzadeh, "Multi-regional Transmission Planning as a Non-cooperative Decision-Making," IEEE Trans. Power Syst., vol. 29, no. 6, pp. 2662–2671, Nov. 2014.

Horizontal coordination
Results (Three-area IEEE-RTS96)



Owner	From-To (Name)	TCap (MW)
TP1	113-215 (u1)	50
TP2	123-217 (u2)	50
TP2	107-203 (u3)	50
TP3	223-318 (u4)	100
TP3	323-121 (u5)	100
TP1	114-124 (u6)	75
TP2	214-224 (u7)	75
TP2	211-220 (u8)	75
TP3	311-320 (u9)	75

TP: Transmission Planner
TCap: Transmission Capacity

Y. Tohidi and M. R. Hesamzadeh, “Multi-regional Transmission Planning as a Non-cooperative Decision-Making,” IEEE Trans. Power Syst., vol. 29, no. 6, pp. 2662–2671, Nov. 2014.

Horizontal coordination
Results (Three-area IEEE-RTS96)

TP2

(1,0,1,1,1,0,0,0,1) → (1,0,0,1,1,0,0,0,1)

Region	Status quo	Cooperative (1,0,1,1,1,0,0,0,1)	Non-cooperative (1,0,0,1,1,0,0,0,1)
All-three	IC = 0 OC = 1, 385, 891 Total = 1, 385, 891	IC=586 OC=1, 385, 248 Total=1, 385, 834	IC=456 OC=1, 385, 401 Total=1, 385, 857
Region 1	IC = 0 OC = 462, 057 Total = 462, 057	IC=130 OC=461, 722 Total=461, 930	IC=130 OC=461, 865 Total=461, 995
Region 2	IC = 0 OC = 230, 951 Total = 230, 951	IC=130 OC=230, 951 Total=231, 081	IC=0 OC=230, 951 Total=230, 951
Region 3	IC = 0 OC = 692, 883 Total = 692, 883	IC=326 OC=692, 575 Total=692, 901	IC=326 OC=692, 585 Total=692, 911

IC: Investment Cost ($)
OC: Operation Cost ($)

Y. Tohidi and M. R. Hesamzadeh, “Multi-regional Transmission Planning as a Non-cooperative Decision-Making,” IEEE Trans. Power Syst., vol. 29, no. 6, pp. 2662–2671, Nov. 2014.

Horizontal coordination
Results (Three-area IEEE-RTS96)

Compensation mechanisms is a system of payment between TPs based on a percentage (α) of the maximum flow in the connecting lines.

	(1,0,0,1,1,0,0,0,1)	(1,0,0,1,1,0,0,0,1)	(1,0,1,1,1,0,0,0,1)
Region	$\alpha = 0.02$	$\alpha = 0.04$	$\alpha = 0.06$
All-three	IC=456 OC=1, 385, 401 Total=1, 385, 857	IC=456 OC=1, 385, 401 Total=1, 385, 857	IC=586 OC=1, 385, 248 Total=1, 385, 834
Region 1	IC=130 OC=462, 075 Total=462, 205	IC=130 OC=462, 160 Total=462, 290	IC=130 OC=462, 124 Total=462, 254
Region 2	IC=0 OC=230, 294 Total=230, 294	IC=0 OC=230, 017 Total=230, 017	IC=130 OC=229, 681 Total=229, 811
Region 3	IC=326 OC=693, 022 Total=693, 348	IC=326 OC=693, 224 Total=693, 550	IC=326 OC=693, 443 Total=693, 769
ΔSC	0	0	23

IC: Investment Cost ($)
OC: Operation Cost ($)
ΔSC: economic benefit of compensation mechanisms ($\Delta SC = SC - SC_0$)
SC_0 : social cost of non-cooperative solution without compensation
SC : social cost of non-cooperative solution with compensation

Y. Tohidi and M. R. Hesamzadeh, "Multi-regional Transmission Planning as a Non-cooperative Decision-Making," IEEE Trans. Power Syst., vol. 29, no. 6, pp. 2662–2671, Nov. 2014.

Horizontal coordination
Conclusion

- The paper proposes **a mathematical model** for multi-TSO transmission planning.
- Without proper compensation mechanism, the non-cooperative transmission planning leads to **inefficient** results as compared to the cooperative solution.
- The paper also proposes **a measure** which can quantify the economic efficiency of a compensation mechanism.

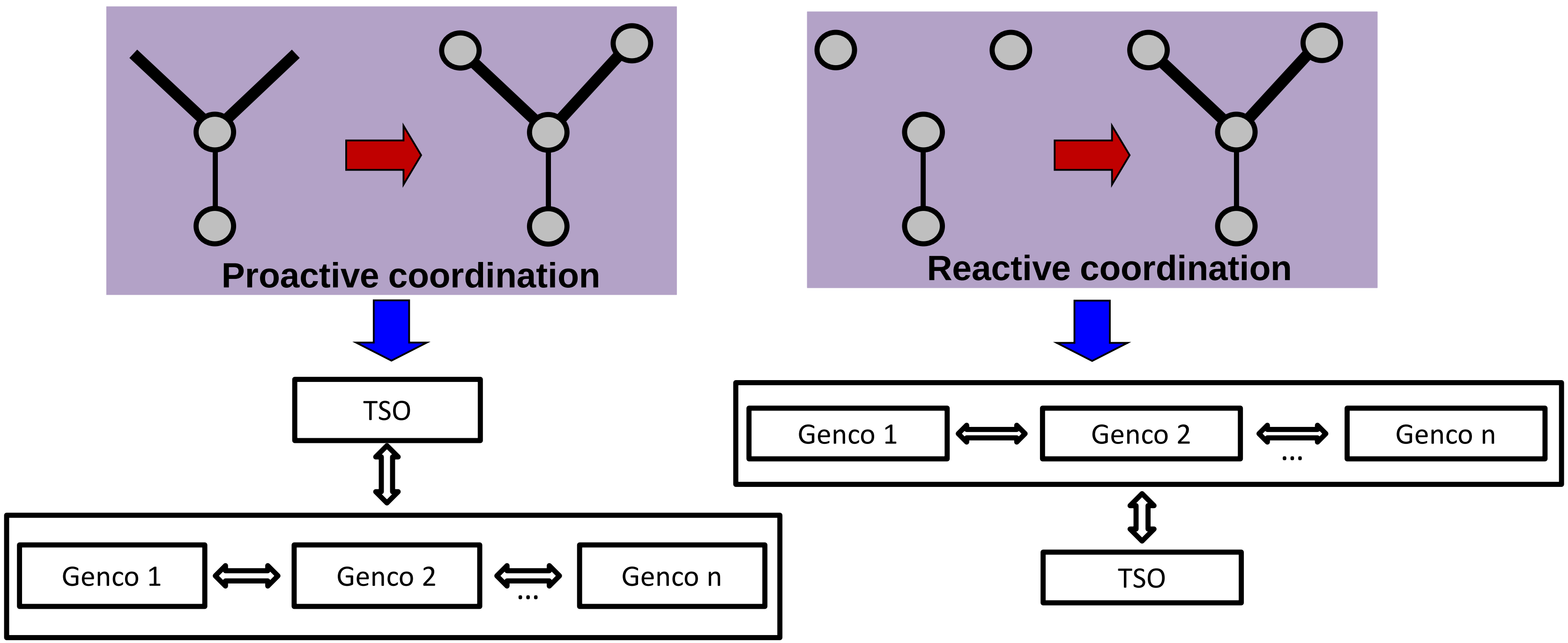
Y. Tohidi and M. R. Hesamzadeh, "Multi-regional Transmission Planning as a Non-cooperative Decision-Making," IEEE Trans. Power Syst., vol. 29, no. 6, pp. 2662–2671, Nov. 2014.

Vertical Coordination

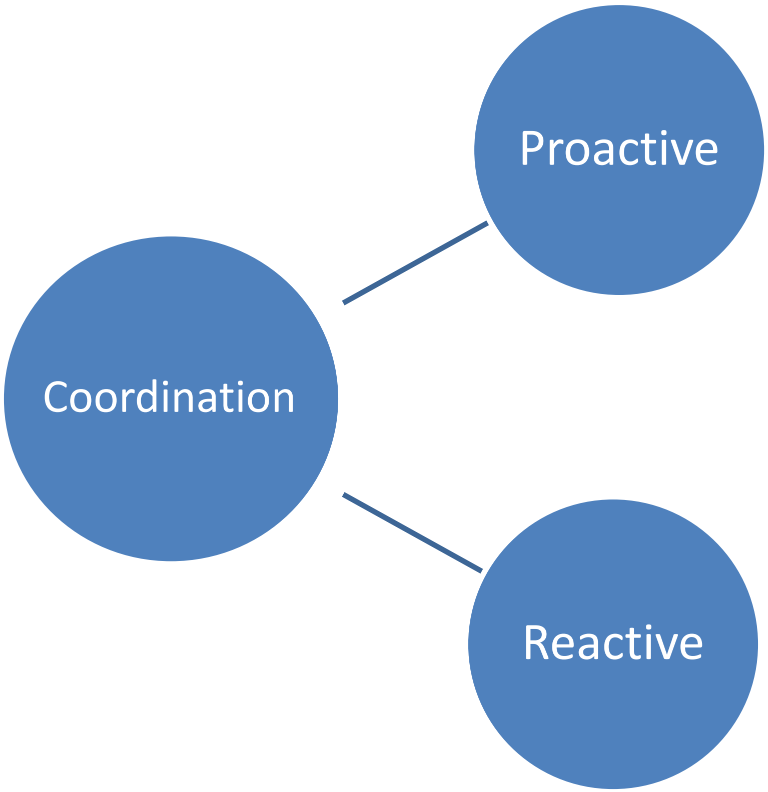
- **Issue:** Substantial sunk investments on generation and transmission are done by different entities in liberalized power markets. How should such sunk investments be vertically coordinated?
- Examples:
  - In Germany, the regulator decides where in the Baltic or North Sea wind parks are to be built and which connection line is to be built (centralized regime).
  - A decentralized regime in Great Britain is implemented.
  - RTE publishes a network development plan which includes the potentially available capacity for new generation (a proactive approach).
- **Contribution:** Modelling of generation and transmission investment planning problems in different levels of decision making

Vertical Coordination

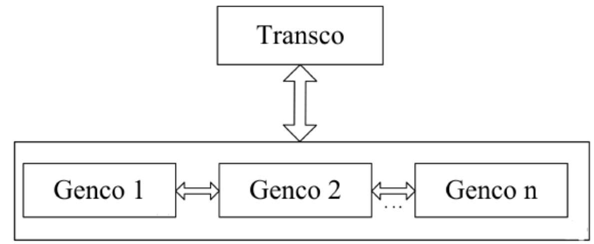
- **Structure of the game**



Vertical coordination
Method



- MIBLP

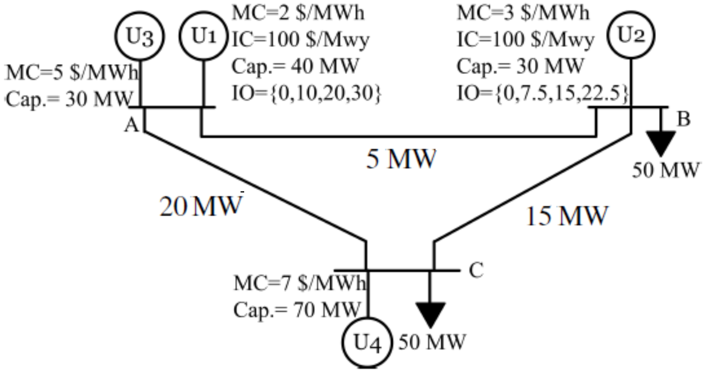


Sequential-move Game

- MILP

Y. Tohidi, M. Hesamzadeh, and F. Regairaz, "Sequential Coordination of Transmission Expansion Planning with Strategic Generation Investments," under revision by IEEE Transactions on Power Systems.

Vertical coordination Results (3-node)



The investment cost of expansion of transmission system is 200 $/MWy for all of the lines.

	EGC (MW)		ETC (MW)			SC
	U1	U2	AB	AC	BC	(M$)
SQ	-	-	-	-	-	3.15
EC	30	0	0	10	15	2.02
RC	0	0	0	6.67	8.33	2.81
PC	20	0	0	10	7.5	2.30

- with reduced generation capacity (by half)

	EGC (MW)		ETC (MW)			SC
	U1	U2	AB	AC	BC	(M$)
SQ	-	-	-	-	-	4.86
EC	15	11.25	5	0	0	3.42
RC	5	7.5	5	0	0	4.05
PC	5	0	5	0	0	4.16

SQ: Status-quo
EC: Efficient Coordination
RC: Reactive Coordination
PC: Proactive Coordination
SC: Social Cost
EGC: Expanded Generation Capacity
ETC: Expanded Transmission Capacity

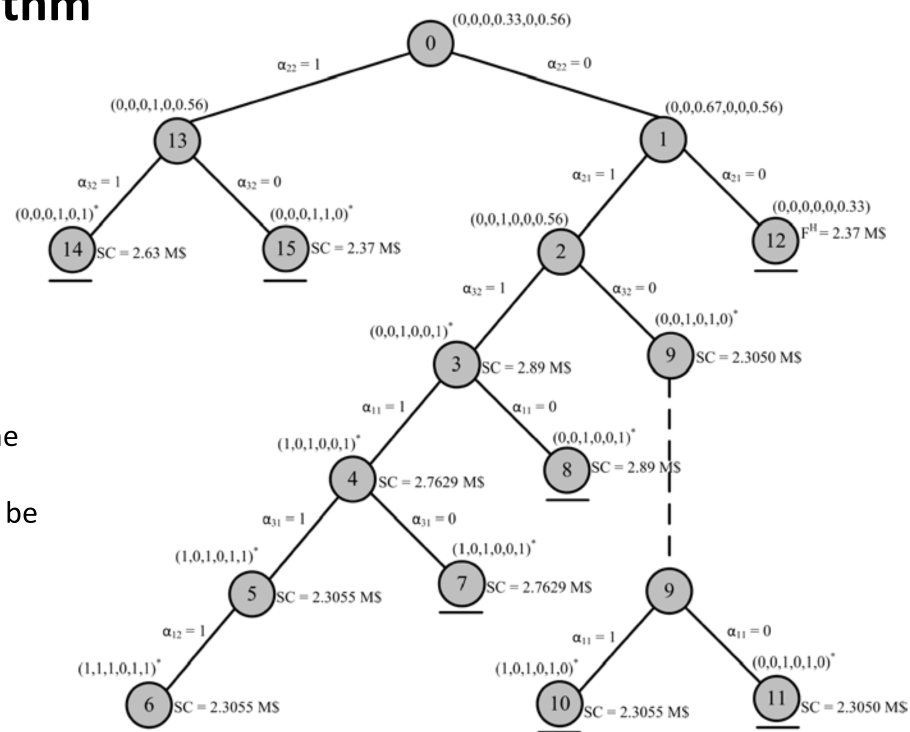
Y. Tohidi, M. Hesamzadeh, and F. Regairaz, "Sequential Coordination of Transmission Expansion Planning with Strategic Generation Investments," under revision by IEEE Transactions on Power Systems.

Vertical Coordination

Parallelized Moore-Bard algorithm

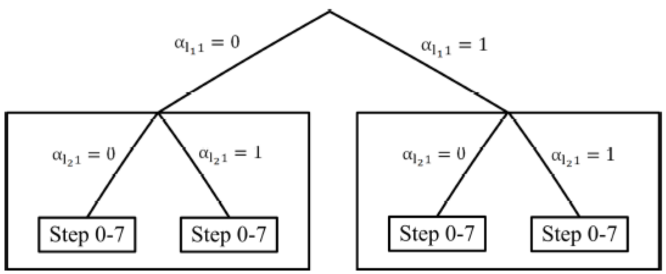
SC(7), SC(8) > SC(6)
SC(10), SC(11), SC(14), SC(15) > SC(9)

- Can be parallelized by dividing the tree between the computing cores (Done!)
- The performance improves if the best solution can be communicated between cores (Future work).



Vertical coordination Results (IEEE-RTS96)

Parallel Moore-Bard Algorithm (P-MBA)



The P-MBA on 4 cores.

Number of Cores	Run time (hours)
1	*
2	63
4	43
8	23

* Not found after three days of simulation.

	EGC (MW)			TEGC (MW)	GIC (M$)	TETC (MW)	TIC (M$)
	U1	U2	U3				
EC	0	300	147.75	447.75	0.045	393.75	1.47
RC	0	300	98.5	398.5	0.040	1066.22	3.03
PC	57	300	98.5	455.5	0.045	0	0

	Profit (M$)			Average Price ($/MWh)	SC (M$)
	U1	U2	U3		
SQ	1.19	2.32	0.68	21	76.28
EC	0	8.54	0.57	5.4	63.48
RC	0.29	8.12	0.82	5.8	67.77
PC	0.61	8.75	0.69	6.9	74.28

SQ: Status-quo
EC: Efficient Coordination
RC: Reactive Coordination
PC: Proactive Coordination
SC: Social Cost
EGC: Expanded Generation Capacity
TEGC: Total Expanded Generation Capacity
GIC: Generation Investment Cost
TETC: Total Expanded Transmission Capacity
TIC: Transmission Investment Cost

Y. Tohidi, M. Hesamzadeh, and F. Regairaz, "Sequential Coordination of Transmission Expansion Planning with Strategic Generation Investments," under revision by IEEE Transactions on Power Systems.

Vertical coordination Results (IEEE 118-bus)

Number of Cores	Algorithm	Run time (hours)
1	P-MBA	*
	Heuristic Technique A	*
	Heuristic Technique B	*
2	P-MBA	*
	Heuristic Technique A	71
	Heuristic Technique B	*
4	P-MBA	*
	Heuristic Technique A	46
	Heuristic Technique B	57
8	P-MBA	*
	Heuristic Technique A	33
	Heuristic Technique B	44

* Not found after three days of simulation.

Y. Tohidi, M. Hesamzadeh, and F. Regairaz, "Sequential Coordination of Transmission Expansion Planning with Strategic Generation Investments," under revision by IEEE Transactions on Power Systems.

Vertical coordination Results (IEEE 118-bus)

	EGC (MW)			TEGC (MW)	GIC (M$)	TETC (MW)	TIC (M$)
	U1	U2	U3				
EC	337.5	98	387.3	822.8	0.4115	4251.34	10.4
RC	225	0	258.2	483.2	0.2416	3759.54	8.3
PC	*	*	*	*	*	*	*
PC (4A)	225	0	387.3	612.3	0.3061	4656.74	10.6
PC (4B)	225	0	387.3	612.3	0.3061	4656.74	10.6

* Not found after three days of simulation.

	Profit (M$)			Average Price ($/MWh)	SC (M$)
	U1	U2	U3		
SQ	9.79	3.95	4.48	20	1174.1
EC	5.64	0	3.94	12	406.84
RC	5.98	0	2.31	15.4	522.32
PC	*	*	*	*	*
PC (4A)	5.88	0	2.47	15.1	483.19
PC (4B)	5.88	0	2.47	15.1	483.19

* Not found after three days of simulation.

SQ: Status-quo
EC: Efficient Coordination
RC: Reactive Coordination
PC: Proactive Coordination
SC: Social Cost
EGC: Expanded Generation Capacity
TEGC: Total Expanded Generation Capacity
GIC: Generation Investment Cost
TETC: Total Expanded Transmission Capacity
TIC: Transmission Investment Cost

Y. Tohidi, M. Hesamzadeh, and F. Regairaz, "Sequential Coordination of Transmission Expansion Planning with Strategic Generation Investments," under revision by IEEE Transactions on Power Systems.

Vertical coordination
Conclusion

- **Modeling** the **proactive** and **reactive** coordinations as MIBLP and MILP.
- **Comparing** the results of **reactive** and **proactive** coordinations to the **efficient** coordination result.
- **Proposing a parallelized Moore-Bard algorithm (P-MBA)** to solve the MIBLP model with discrete variables in both levels.
- The numerical results clearly show the **importance of sequence of investments** in transmission and generation sectors.

Y. Tohidi, M. Hesamzadeh, and F. Regairaz, "Sequential Coordination of Transmission Expansion Planning with Strategic Generation Investments," under revision by IEEE Transactions on Power Systems.

Future Work

- ❑ Expanding the previous models and develop a transmission-generation planning model in the context of multi-TSO multi-Genco
- ❑ Designing coordination mechanisms for this model
- ❑ Improving the computational performance