Reliability Assessment of Power Systems with Optimal Midterm Hydro and Natural Gas Allocations (Application of stochastic unit commitment)

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Outline

- Introduction to Stochastic SCUC
- Stochastic Long-term SCUC Model
- Reliability Calculation for the Long-term SCUC
- Long-term SCUC for Interdependent Infrastructures
- Conclusions

Long-term SCUC

- Coordination between fuel allocation, emission allowance combined with other natural resources and the long-term generation scheduling
- Impact of forced outage rates and load forecast errors on long-term scheduling
- Provide a wider range of options to manage the security in short-term and real-time power system operations

Stochastic SCUC Model

- Uncertainty in power system operations
  - Unscheduled outages in power systems
    - generators
    - transmission lines
  - Long-term load forecast error
  - Intermittent resource availability

Stochastic Long-term SCUC

- Monte Carlo method is adopted to generate a set of scenarios, each of which represents unscheduled outages, load forecast errors, and intermittency of resources in the long-term power system operation.
- Scenario reduction and scenario aggregation techniques are used to build an easy-to-solve stochastic long-term SCUC model.
- DC power flow is included for the network (gas, electricity) models.
- Lagrangian relaxation is used to decompose coupling constraints among scenarios. Dual decomposition is used as a price-based coordination approach to solve long-term fuel allocation and emission allowance constraints for each scenario.

Stochastic Long-term SCUC

- Objective function

$$\min \sum_{s=1}^{S} P_s \sum_{p=1}^{NP} \sum_{t=1}^{NT} \sum_{i=1}^{NG} [F_{c,itp}(P_{itp}^s * I_{itp}^s) + SU_{itp}^s + SD_{itp}^s]$$

- System constraints
  - System load balance

$$\sum_{i=1}^{NG} P_{itp}^s * I_{itp}^s = P_{D,tp}^s \quad \forall t, \forall p, \forall s$$

  - System reserve constraints

$$\sum_{i=1}^{NG} R_{S,itp}^s * I_{itp}^s \geq R_{S,tp}^s \quad \forall t, \forall p, \forall s$$

$$\sum_{i=1}^{NG} R_{O,itp}^s * I_{itp}^s \geq R_{O,tp}^s \quad \forall t, \forall p, \forall s$$

Unit constraints

- Real power generation limits

$$P_{i,\min} I_{itp}^{s} \le P_{itp}^{s} + R_{S,itp}^{s} + R_{O,itp}^{s} \le P_{i,\max} I_{itp}^{s} \qquad \forall i, \forall t, \forall p, \forall s$$

- Ramping un / down constraints

$$P_{itp}^{s} - P_{i(t-1)p}^{s} \le [1 - I_{itp}^{s}(1 - I_{i(t-1)p}^{s})]UR_i + I_{itp}^{s}(1 - I_{i(t-1)p}^{s})P_{i,\min}$$

$$P_{i(t-1)p}^{s} - P_{itp}^{s} \le [1 - I_{i(t-1)p}^{s}(1 - I_{itp}^{s})]DR_i + I_{i(t-1)p}^{s}(1 - I_{itp}^{s})P_{i,\min}$$

- Minimum on / off time constraints

$$[Xon_{i(t-1)p}^{s} - T_i^{on}] * (I_{i(t-1)p}^{s} - I_{itp}^{s}) \ge 0$$

$$[Xoff_{i(t-1)p}^{s} - T_i^{off}] * (I_{itp}^{s} - I_{i(t-1)p}^{s}) \ge 0 \qquad \forall i, \forall t, \forall p, \forall s$$

- Fuel constraints for group of units

$$F_{g,i}^{\min} \le \sum_{i \in m} \sum_{p=1}^{NP} \sum_{t=1}^{NT} [F_{f,i}(P_{itp}^{s}) * I_{itp}^{s} + SU_{f,itp}^{s} + SD_{f,itp}^{s}] \le F_{g,i}^{\max} \qquad \forall m$$

- Emission constraints for group of units

$$\sum_{i\in np=1}^{NP}\sum_{t=1}^{NT}[E_{e.i}^{ET}(P_{itp}^{s})*I_{itp}^{s}+SUET_{e,itp}^{s}+SDET_{e,itp}^{s}]\le E_{g.i}^{ET,\max} \qquad ET=\{SO_2,NO_x\}$$

- Network security constraints
  - DC power flow

$$PL_{l,tp}^{s}=(\theta_m-\theta_n)/x_{mn} \qquad \forall l,\forall t,\forall p,\forall s$$

  - Transmission flow constraints

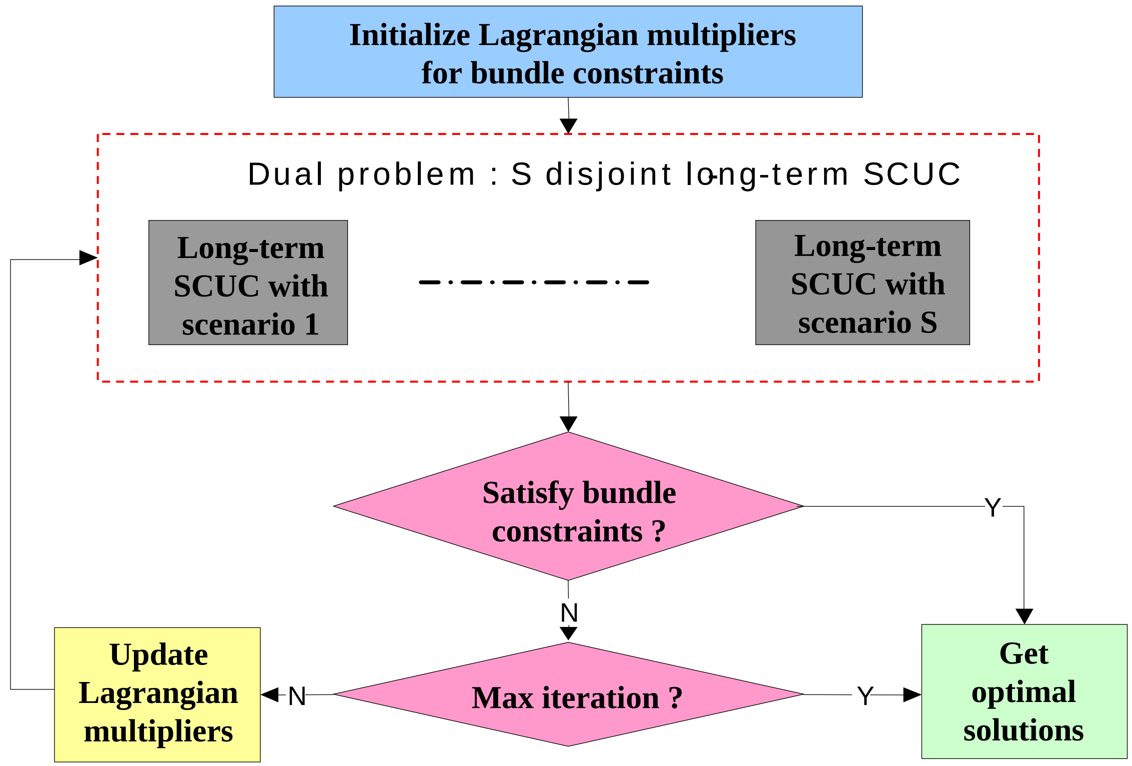
$$-PL_{l.\max}\le PL_{l,tp}^{s}\le PL_{l,\max} \qquad \forall l,\forall t,\forall p,\forall s$$

- Bundle constraints

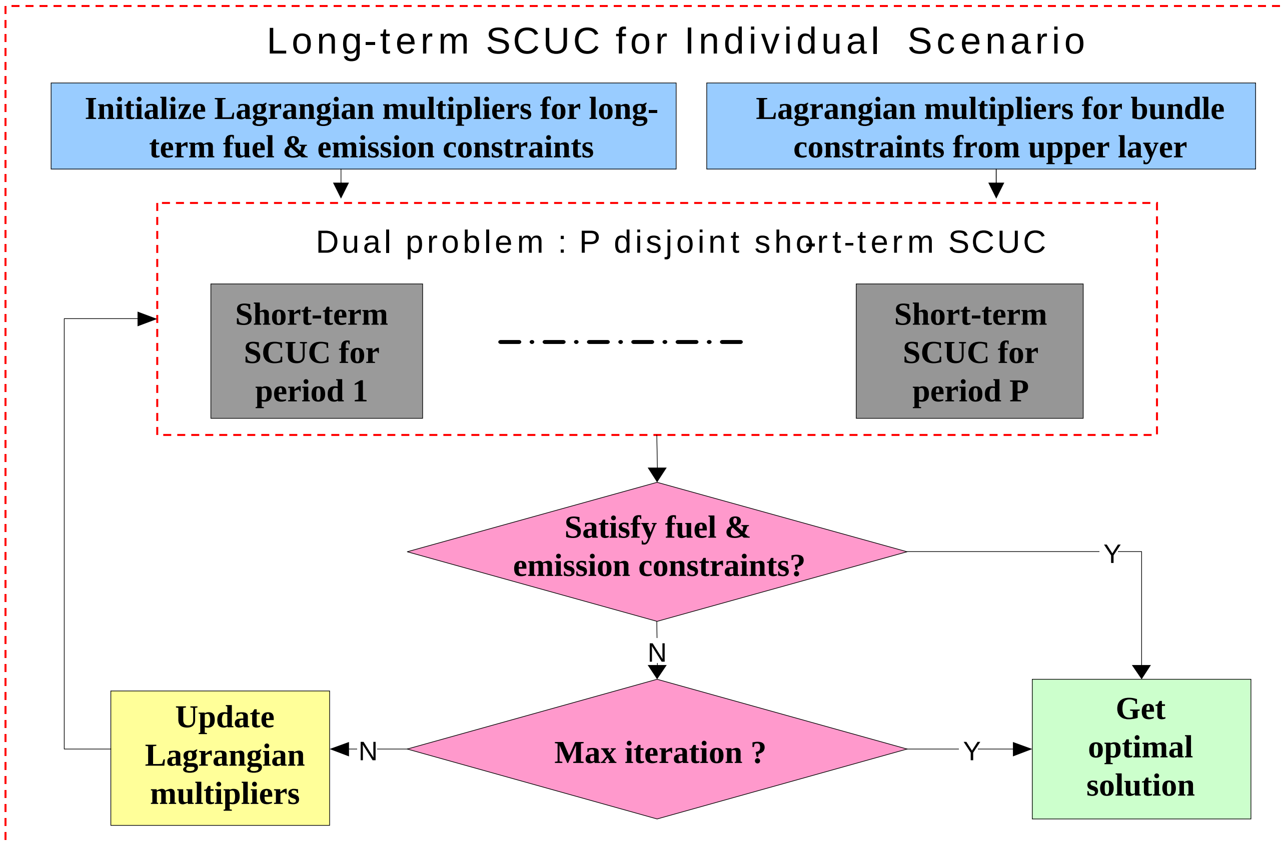
$$B(s,P,\tau)=B(s',P,\tau)=\Omega_{P\tau}\Rightarrow I_{itp}^{s}=I_{itp}^{s'}=c_{itp} \qquad c_{itp}=\frac{\sum_{s\in B(s,P,\tau)=\Omega_{P\tau}} P_s*I_{itp}^{s}}{\sum_{s\in B(s,P,\tau)=\Omega_{P\tau}} P_s}$$

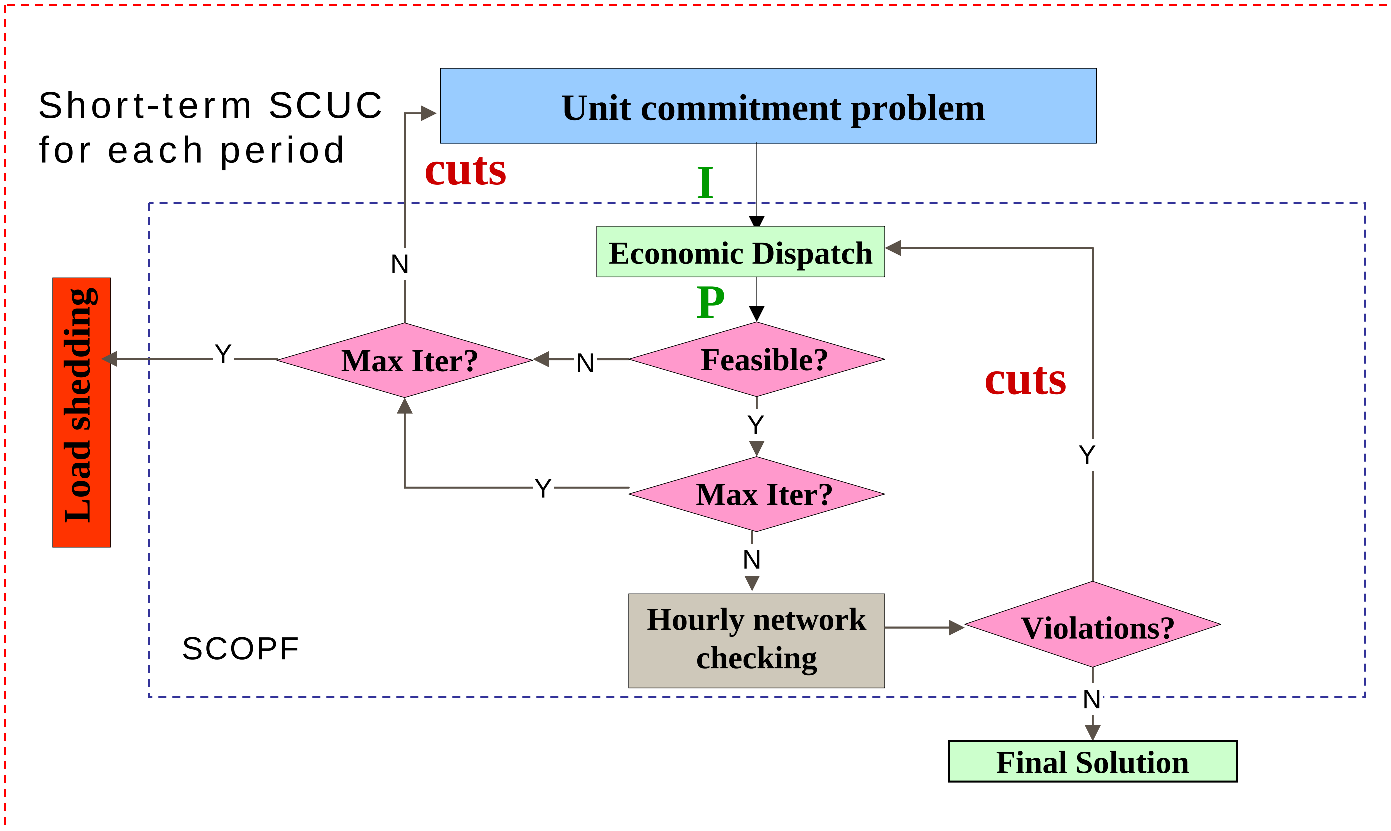
Decomposition Methodology

- Decomposition of bundle constraints among scenarios



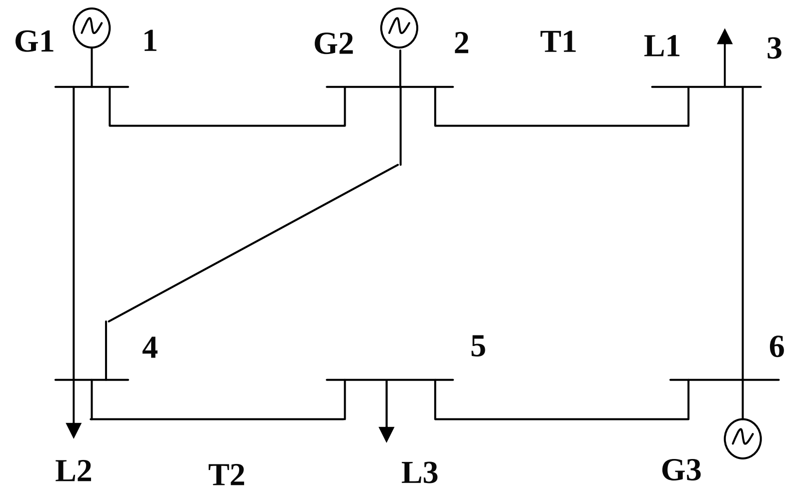
- Decomposition of Long-term fuel and emission constraints





Short-term SCUC
for each period
Unit commitment problem
cuts
I
Economic Dispatch
P
Load shedding
Y
Max Iter?
N
N
Feasible?
Y
Max Iter?
Y
N
cuts
Y
Hourly network checking
Violations?
SCOPF
N
Final Solution

Six-bus Test System

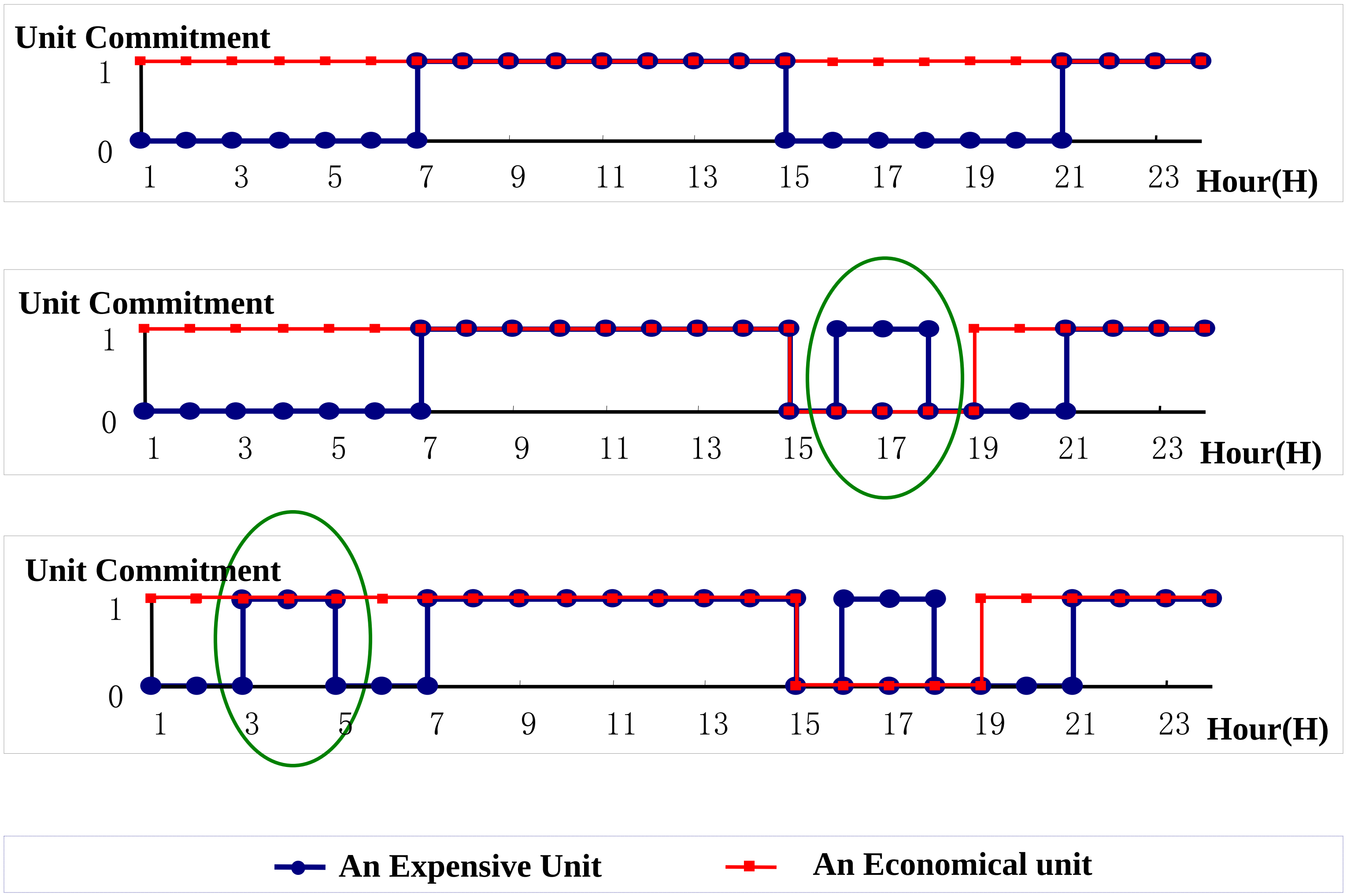


- Case 1: Base case without any uncertainties.
- Case 2: Consider random generator failures and transmission line outages, system load is the same as base case.
- Case 3: Consider random generator failures and transmission line outages, as well as load forecast error.

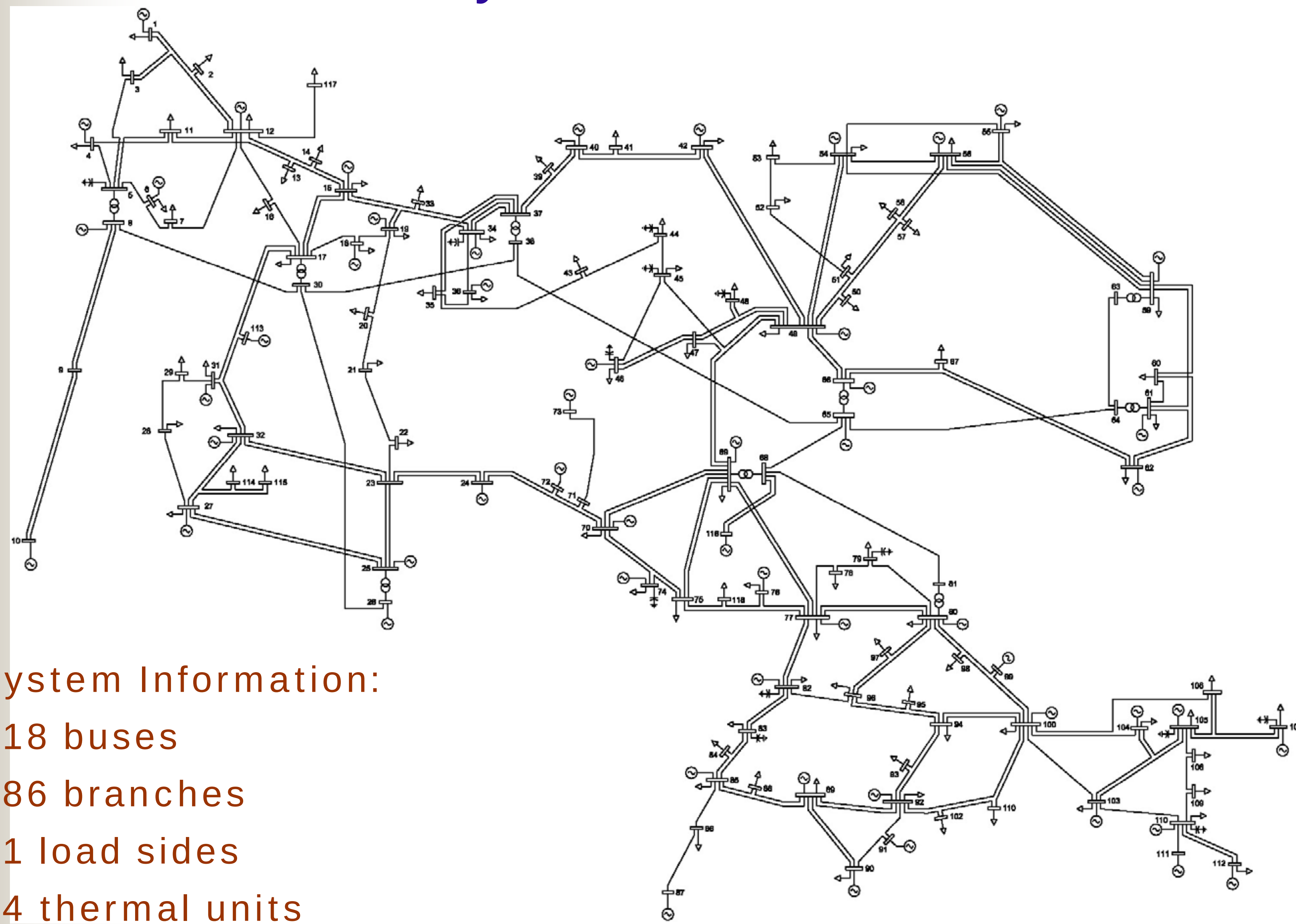
Case 1

Case 2

Case 3



IEEE 118-bus System



System Information:

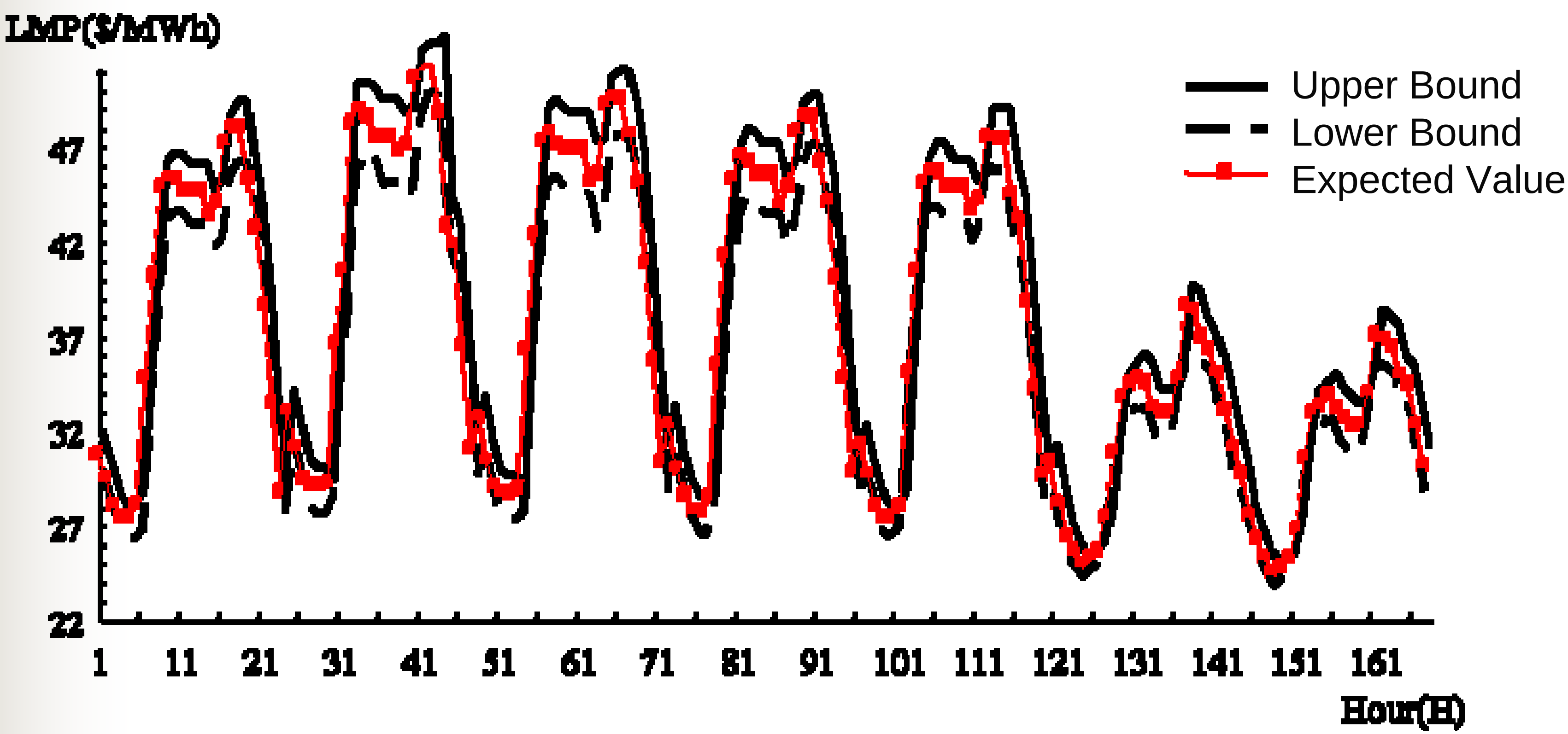
118 buses

186 branches

91 load sides

54 thermal units

LMP at bus 1 in the 3rd week



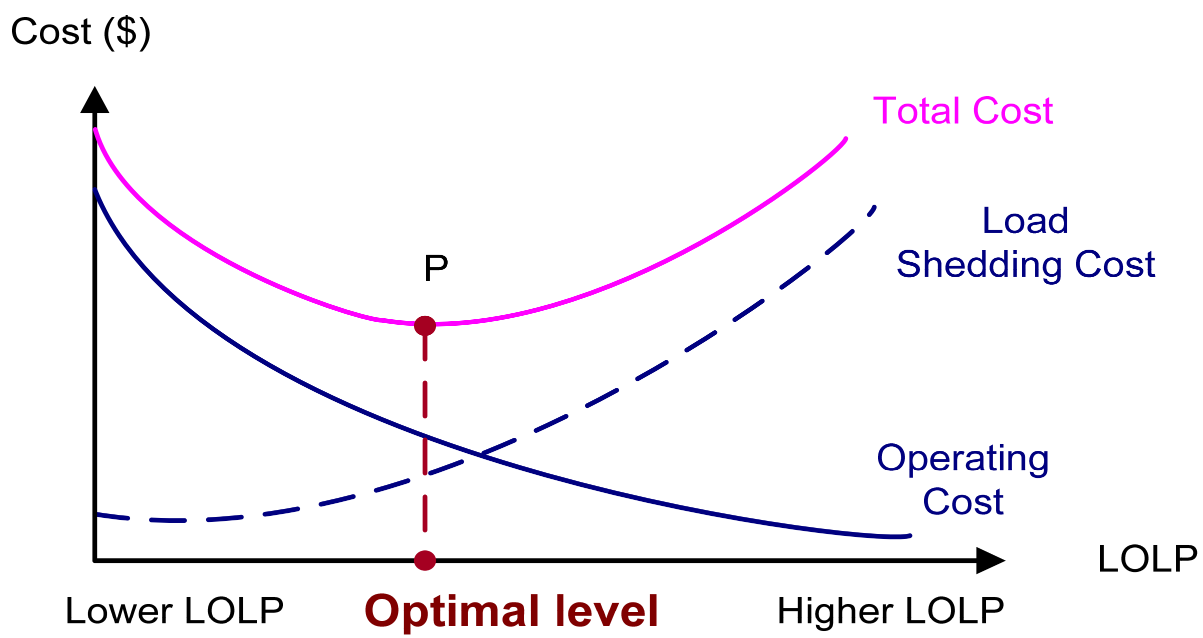
IEEE 1168-bus System

- 169 units and 1474 branches.
- Annual peak load is 22350 MW.
- Four week case study.

FUEL CONSUMPTION FOR EACH SCENARIO (CASE C)

EXP of Fuel Consumption (MBtu)	**Coal**	**Oil**	**Gas**
	7,484,549 ±157,101	1,434,690 ±25,810	4,355,435 ±48,693
EXP of SO_2 Emission (lbs)	**SO_2 (EGp1)**	**SO_2 (EGp2)**	**SO_2 (EGp3)**
	1,347,327 ±28,267	301,167 ±5,418	806,814 ±9,359
EXP of NO_x Emission (lbs)	**NO_x (EGp1)**	**NO_x (EGp2)**	**NO_x (EGp3)**
	765,421 ±16,066	141,457 ±2,543	468,557 ±5,529
Operating Cost ($)	82,405,215 ± 2,127,833		

Variation of costs as a function of reliability



The result represents a minimum total cost while satisfying a certain level of reliability.

Marginal operating cost = Marginal load shedding cost

Reliability Constraints

$$\min \sum_{s=1}^{S} P_s \sum_{p=1}^{NP} \sum_{t=1}^{NT} \{ \sum_{i=1}^{NG} [F_{c,itp}(P_{itp}^{s} * I_{itp}^{s}) + SU_{itp}^{s} + SD_{itp}^{s}] + \sum_{b=1}^{NB} C_{b,tp}^{s} * LS_{b,tp}^{s} \}$$

$$LS_{b,tp}^{s} = P_{b,tp}^{s} - \sum_{i \in B_b} P_{i,tp}^{s} - \sum_{l \in L_b} PL_{l,tp}^{s} \quad \forall t, \forall p, \forall s$$

$$C * LSIDX_{tp}^{s} \le LS_{b,tp}^{s} \le P_{b,tp}^{s} * LSIDX_{tp}^{s} \quad \forall t, \forall p, \forall s, \forall b$$

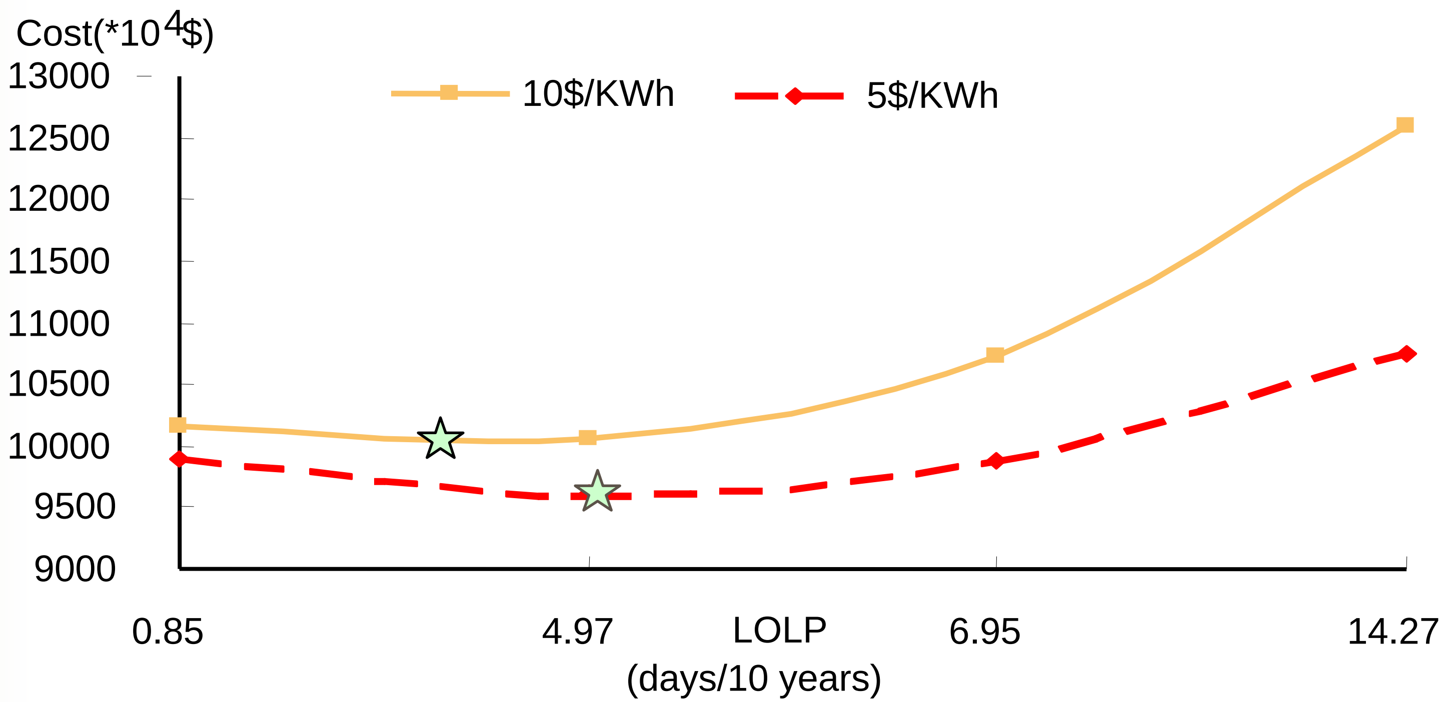
$$LSIDX_{tp}^{s} \in \{0,1\} \quad C: a \quad small \quad positive \quad threshold$$

$$LOLP^{s} = \frac{\sum_{p=1}^{NP} \sum_{t=1}^{NT} LSIDX_{tp}^{s}}{NT * NP} \le LOLP_{fix} \qquad \forall s$$

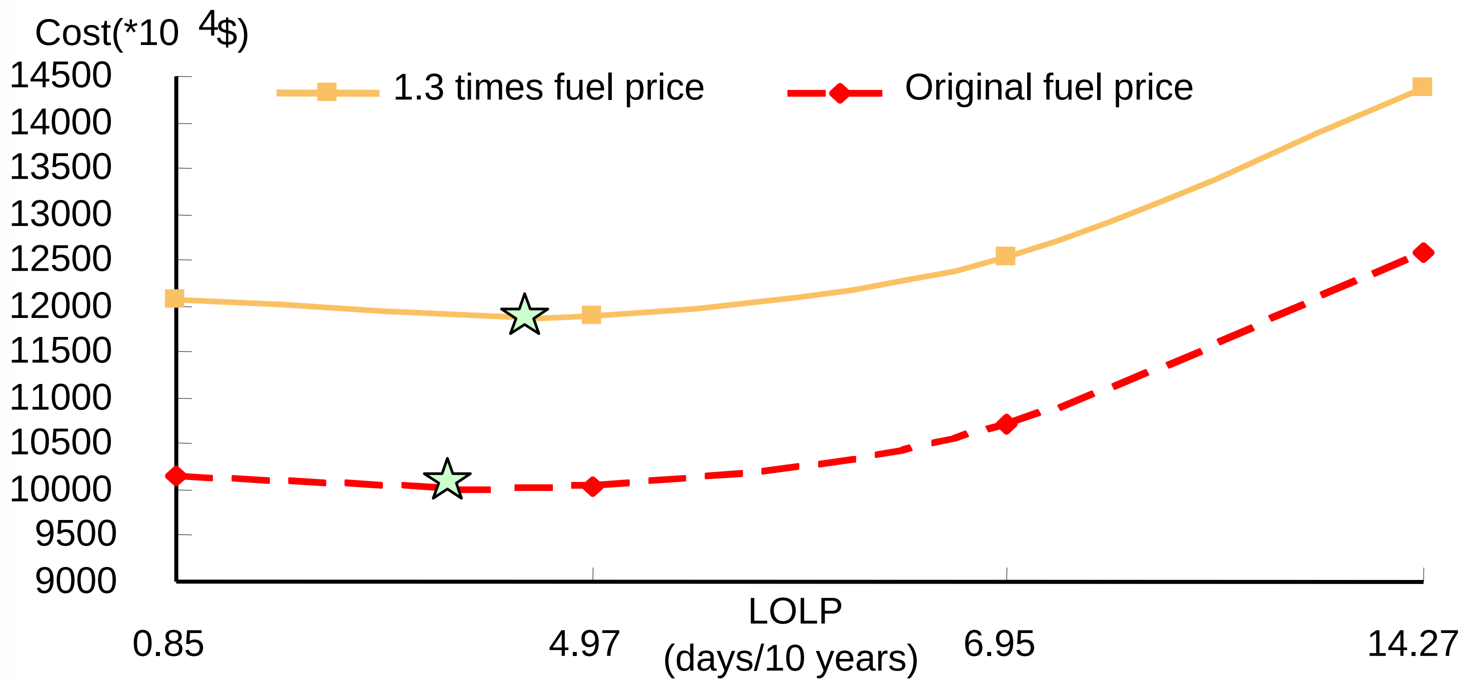
IEEE 118-bus system case study

LOLE(in 10 years)		1 day	5 days	10 days	15 days	No Reliability
Operating cost (*$10^4$$)		9623.89	9136.65	9027.18	8880.03	8786.37
EENS (MW)		532.21	920.85	1692.74	3714.02	7040.22
Max LOLE (in 10 years)		0.85 day	4.97 days	6.95 days	14.27 days	31.7 days
Min reserve (MW)		905.33	579.98	471.25	382.28	254.21
Coal (MBtu)		72,443,639	74,059,858	74,112,301	74,279,656	73,987,725
Oil (MBtu)		6,475,901	5,945,081	4,904,175	4,426,361	3,887,508
Gas (MBtu)		12,111,537	9,675,367	9,572,179	9,784,396	11,346, 726
SO_2	EGp_1 (Lbs)	7,545,283	7,574,098	7,617,717	7,619,974	7,962,311
	EGp_2 (Lbs)	194,025	136,119	120,422	118,074	79,479
	EGp_3 (Lbs)	1,534,584	943,378	942,819	948,722	1,427,691
NO_x	EGp_1 (Lbs)	3,029,639	3,018,115	3,046,682	3,047,591	3,184,927
	EGp_2 (Lbs)	93,619	74,441	64,174	47,237	31,791
	EGp_3 (Lbs)	653,839	377,351	353,122	361,495	571,073

Impact of load shedding price on optimal point



Impact of fuel price on optimal point



Applications to Hydro-Gas Coordination

- ISOs maintain power systems reliability when supplying the hourly load at minimum cost. In this environment, the interdependency of natural gas and electric power systems could affect the security and economics of power systems.
  - For instance, in winter months when residual usages of natural gas increases in some regions, there may be an insufficient level of natural gas available for gas-fired units. Hydro units could be used in such occasions in order to avoid electric load curtailments.
  - However, if the following spring season happens to be dry, water reservoirs utilized in the previous winter would not be replenished. Thus insufficient water resources could lead to the inability of hydro units to supply peak summer loads.

Proposed Methodology

- The reliability assessment for the midterm (several months to one year) optimal water and natural gas usage is analyzed.
- Uncertainty factors, including random outages of system components, future electric power load and gas load forecast error, and future natural water inflow uncertainty, are simulated by the Monte Carlo method and the scenario-based techniques are used to keep the trade-off between computation time and solution accuracy.
- The scheduling horizon is decoupled into period stages (several weeks to one month). The periodical operation policy determines, at the beginning of each period, how much of the water should be used and how much should be stored for the future usage.
- The predefined operation rules are adopted to approximate the actual depletion policy of reservoirs located in a same catchment, which simplify the coupling constraints among successive periods and advantage the decomposition procedure.

- The problem is formulated as a two-stage stochastic programming model for the optimization period of one year.
  - The first-stage is for optimizing the operation for the first month.
  - The second-stage is for optimizing the remaining eleven months for simulating the midterm operation via scenarios .

Problem Formulation

- The objective is to:
  - minimize the social cost, including operation cost (i.e. the production cost, startup and shutdown costs of individual units) and the possible load shedding cost for the entire midterm horizon .

$$
\min \sum_{p=1}^{NPD} \sum_{t=1}^{NT} \left\{ \begin{array}{l} \sum_{i=1}^{NG} \left[F_c\left(P_{itp}\right) \cdot I_{itp} + SU_{itp} + SD_{itp} \right] \\ + \sum_{h=1}^{NH} SU_{htp} + \sum_{b=1}^{NB} \sum_{m=1}^{NM} pv_{b,m} \cdot LS_{btp,m} \end{array} \right\} +
$$

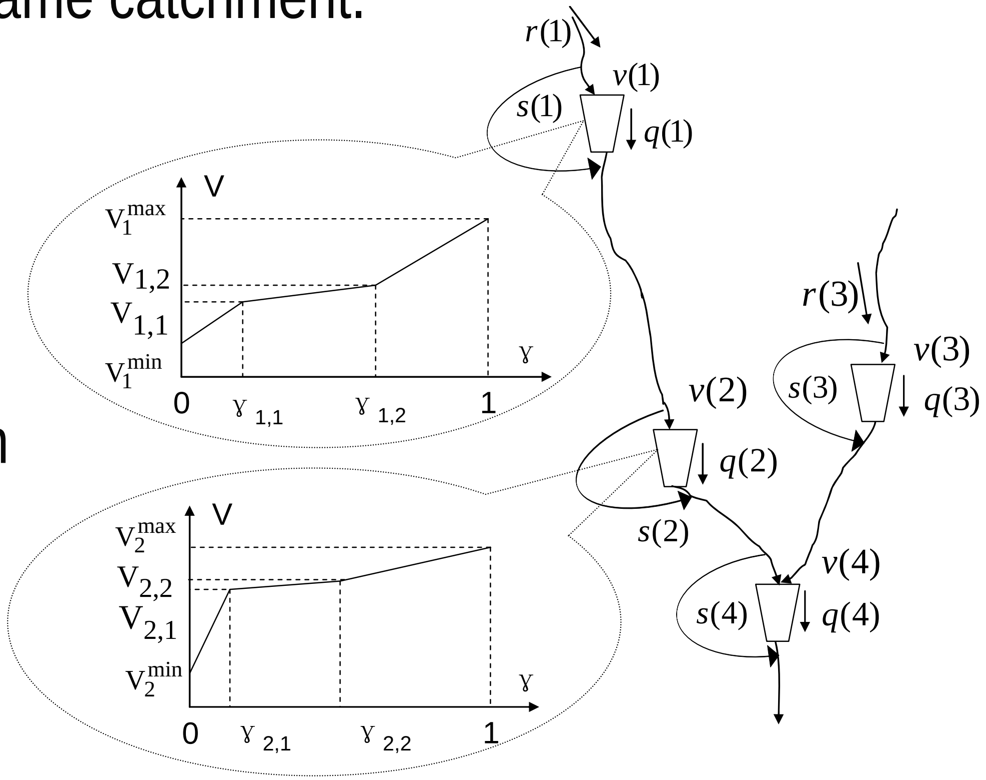
$$
\sum_{s=1}^{NS} p^s \cdot \sum_{p=1+NPD}^{NPS+NPD} \sum_{t=1}^{NT} \left\{ \begin{array}{l} \sum_{i=1}^{NG} \left[F_c\left(P_{itp}^s\right) \cdot I_{itp}^s + SU_{itp}^s + SD_{itp}^s \right] + \\ \sum_{h=1}^{NH} SU_{htp}^s + \sum_{b=1}^{NB} \sum_{m=1}^{NM} pv_{b,m}^s \cdot LS_{btp,m}^s \end{array} \right\}
$$

Constraints

- System power balance constraint.
- Individual generator constraints for various types of units, including ramping up/down rate limits, minimum on/off time limits, generation unit capacity limits
- Individual cascaded hydro unit constraints, including reserve volume limits, water balance constraint, water discharge limits
- Power transmission constraints, including dc network security constraints and phase shifter angles limits.
- Natural gas transmission constraints, including gas contract limits, gas usage limits, pipeline and compressor transmission capability limits, etc.
- Reliability constraints including load shedding limits at each bus and each time period in each scenario, and LOLE limits.
- Reservoir volume coupling constraints for two consecutive periods, which indicates that the terminal volume at the end of previous period should be the initial volume at the beginning of successive period

Midterm Reservoir Operation Rule

- A set of curves describing the relationship between the global parameter (one global parameter for each catchment) and each reservoir volume in the same catchment.
- The operation rule is input data, which can be designed based on historical inflow records or non-linear optimization model.
- The operation rule does not need to be convex.



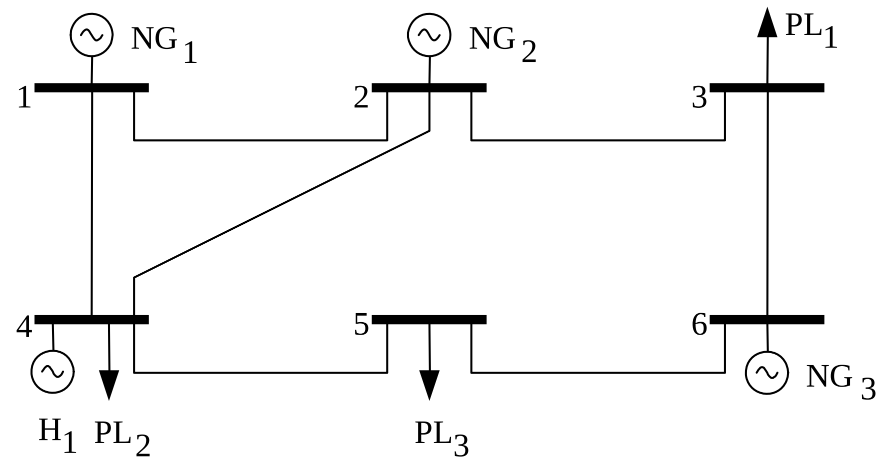
Stochastic Solution

- The midterm horizon is divided into several periods, with the relaxation of reservoir volume coupling limits linking successive periods.

- Coupling constraints, ramping up/down rate limits, minimum on/off time constraints and delayed water discharge from upper reservoirs to lowers, which link successive periods, are managed based on one of the following two strategies The difference between the two signifies the tradeoff between speed and accuracy. We adopted the second alternative.
  - Constraints on ramping up/down rate, minimum on/off time constraints and delayed water discharge from upper reservoirs to lowers, which link successive periods, will be ignored. Accordingly, the short-term unit commitment problem can be solved for each period independently. The application of parallel processing will speed up the solution. However, the accuracy may suffer slightly.
  - Short-term unit commitment subproblems are solved sequentially. That is, the results of the short-term unit commitment for the first period provide initial conditions for the second period. In this case, ramping up/down rate and minimum on/off time constraints will be satisfied within each period by unit commitment.

Case Studies

- A 6-bus system
  - 3 gas-fired units, 1 hydro unit and 7 transmission lines
  - The system is tested for a one-year case (from November to the October in the next year) with the annual peak power load of 330MW and annual peak gas load of 6000 kcf .
  - The maximum allowed load shedding for each load bus is set to be the load value at designated bus, with the VOLL of 5000$/MWh for the first 10% of load at designated bus and 2000$/MWh for the remaining.



- Two cases are studied to illustrate the effect of midterm water and gas optimal usage on power systems reliability
  - Case 1: A deterministic solution is presented and its impact on the system reliability is discussed. The optimization of deterministic model utilizes as much water as possible to supplement the natural gas usage in the winter season (November-January with highest gas loads). The impact of the deterministic solution on the system reliability is considered by optimizing a scenario-based stochastic model for the remaining months of February-October by utilizing terminal volumes at the end of January as the initial condition.
  - Case 2: The proposed two-stage stochastic optimization model is discussed. The first-stage covers the first month, and the second-stage includes the rest 11 months via scenarios. System component outages, power and gas load uncertainties, and natural water inflow uncertainties are all taken into consideration.

- Case 1:
  - Due to the limited capability of gas network, the natural gas required by gas-fired generating units cannot be transported to corresponding nodes by the gas transmission system.
  - The water resource is the alternative to cover the load. The terminal reservoir volume at the end of winter is not restricted, thus water resource in the reservoir is used as much as possible, and the terminal reservoir volume at the end of the winter reaches its minimum value $60*10^4$ m^3 .

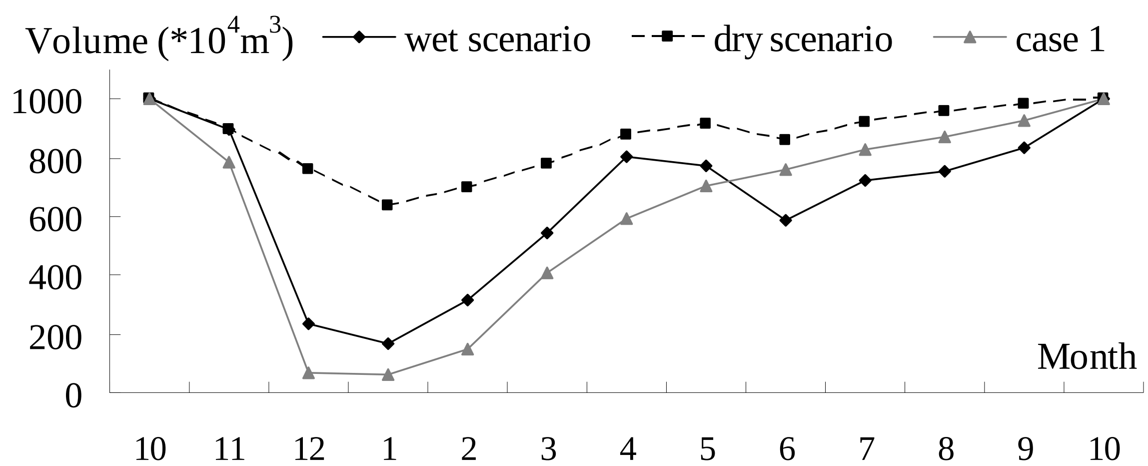
Social Cost ($)		12,141,356.75
Load Shedding (MWh)		411.42
# of Hours LS Occurs		56
Volume at the end of each month ($*10^4$ m^3)	11	860.34
	12	65.83
	1	60.00

- Using $60*10^4$ m^3 , the terminal volume at the end of the winter, as the initial condition for the following seasons, and 1000 $*10^4$ m^3 as the terminal volume for the rest 9 months.
- The total social cost is $39,585,164.34 (i.e. 12,141,356.75 + 27,443,807.59) with the load shedding of 460.91MWh and total number of load shedding occurrence of 96.465 hours in one year.

Scenario	Social Cost ($)	LS (MWh)	# of LS Hours
1	27,659,311.07	53.62	57
2	27,425,028.63	37.29	35
3	27,678,604.15	53.10	39
4	27,551,233.52	54.52	43
5	27,296,860.88	38.91	47
6	27,672,777.70	43.15	29
7	27,608,847.21	57.60	48
8	28,646,885.12	45.15	40
9	26,587,588.48	43.03	33
10	28,715,483.62	76.87	54
11	27,667,616.62	57.55	50
12	26,212,352.22	60.16	49
Expected	27,443,807.59	49.49	40.465

- Case 2:
  - The proposed two-stage stochastic optimization is considered for optimizing the midterm water and gas usage with uncertainties.
  - The load shedding is reduced to 440.90 MWh from 460.91MWh, and the total number of load shedding occurrence is reduced to 71.07 hours in one year from 96.465 hours in one year.
  - Water resource stored in the reservoir, previously fully utilized in the winter in case 1, now is partly allocated in the summer for peak-shaving, which reduces the load shedding occurrence in the summer and the social cost is reduced by 5.08% (i.e., 39,585,164.34 –37,572,145.9 / 39,585,164.34).

- In case 1, the water resource stored in the reservoir is used as much as possible when the future natural water inflow situation is not considered.
- Two scenarios, a dry and a wet year, shows that water used in the winter has to be limited, to ensure enough water for peaking-shaving in case of a dry weather in the future.
- The results reveal the necessity of incorporating the two-stage stochastic optimization model for the midterm water and gas management policies to enhance the systems reliability.



- IEEE 118-bus system
  - 54 fossil units, 12 gas-fired units, 7 hydro units, 186 branches, and 91 demand sides.
  - Hydro units 1-4 belongs to one catchment, and 5-7 belongs to another.
  - The system is tested for a one-year case (from November to the October in the next year) with the annual peak power load of 8,600 MW and annual peak gas load of 31,000 kcf.

- For the proposed two-stage stochastic optimization model, the load shedding is reduced to 14,988.16 MWh from 16,036.86 MWh.
- The optimal allocation of water resource stored in reservoirs for the midterm horizon reduces the social cost by 2.83%.

First-stage solution (November)					
Social Cost			$54,915,796.54		
LS (MWh)			1,641.65		
Terminal Volume (*10^4 m^3)		Hydro Unit 1		Hydro Unit 5	
		443.985		524.97	
Second-stage solution (December – October)					
Scen	Social Cost ($)	LS (MWh)	Scen	Social Cost ($)	LS (MWh)
1	569,348,058.64	12,709.49	7	638,250,719.88	12,140.42
2	631,623,855.91	15,675.10	8	553,314,423.24	12,541.41
3	575,609,207.51	12,374.16	9	548,171,522.09	14,049.00
4	573,665,664.86	13,381.57	10	579,617,496.76	13,207.50
5	571,984,423.07	12,647.78	11	659,318,818.53	12,121.87
6	639,399,045.85	14,535.15	12	539,828,573.25	13,165.35
Expected Cost	592,150,917.73		Expected LS		13,346.51

Conclusions

- Propose Monte Carlo method to simulate unscheduled outages and load forecast error, and scenario-based techniques to form a stochastic model for the long-term SCUC solution.

- Coordination between fuel allocation, emission allowance combined with other natural resources and long-term generation scheduling.

- Provide long-term planning decisions on energy allocation, fuel consumption, emission allowance, and long-term utilization of generators and transmission capacities.

Conclusions

- A two-stage stochastic programming model for optimizing the midterm water and gas usage uncertainties.
- The reliability criteria are incorporated into the midterm stochastic unit commitment problem in which both the power and the gas network security are checked and uncertain characteristics of power systems including component outages, power and gas load forecast errors, and natural water inflow are considered.
- The proposed stochastic optimization model improves power system reliability and decrease the social cost by optimally allocating natural water and gas usage in a midterm horizon.

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