Transmission Expansion Planning of Systems with Increasing Wind Power Integration

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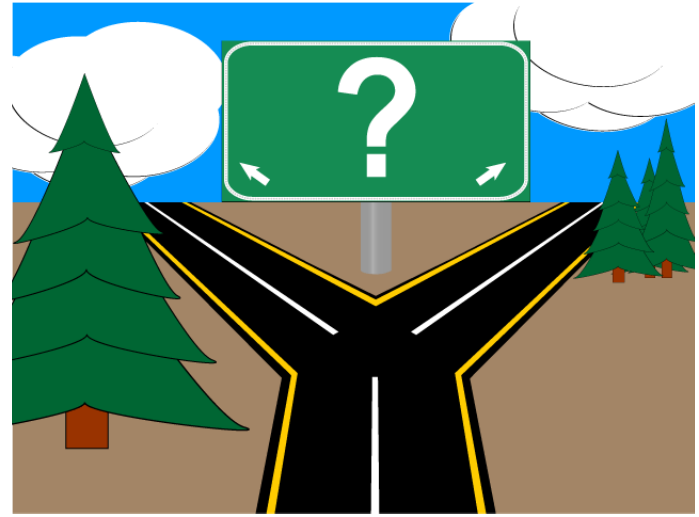
Objective of TEP

The objective of transmission expansion planning (TEP) in deregulated electricity markets is to provide nondiscriminatory and competitive market conditions to all stakeholders, while maintaining power system reliability.

Uncertainties in TEP



1. **Random** uncertainties, such as:
   - load growth;
   - generators operating costs; generators bidding prices;
   - availability of generators; availability of transmission lines;
   - renewables production;
   - etc.
2. **Nonrandom** uncertainties, such as:
   - location of new generators;
   - available transmission expansion investment budget;
   - etc.

Statistics of Uncertainties

- The statistics of random uncertainties can be derived from past observations.

- Nonrandom uncertainties are not repeatable and cannot be statistically represented.

TEP is challenging

The large integration of wind power into modern power systems has made the TEP problem even more challenging, because the greatly increased uncertainties introduced often require new transmission lines in order to maintain a satisfactory level of power system security and adequacy.

Proposed TEP Model

- **Probabilistic** TEP that considers load and wind power generation **uncertainties** as well as **N-1 security** analysis.

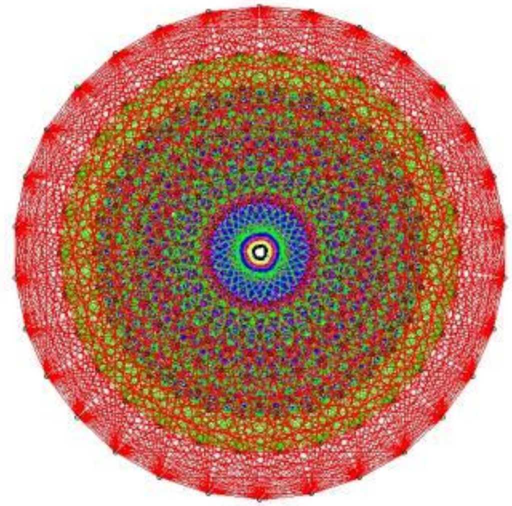
Proposed TEP Model

$$Min\left\{\sum_{(i,j)} IC_{ij} n_{ij} + p_{fe} Pr\left\{\sum_k r_k > L_{max}\right\} E\left(\sum_k r_k\right)\right\}$$

- An **upper bound on total load shedding** ($L_{\max}$) is introduced in order to obtain network solutions that have an acceptable probability of load curtailment.
- $L_{\max}$ is used to find solutions that in fact eliminate the probability the load shedding to be higher than $L_{\max}$ during system peak load.
- The penalty factor p_{fe} is used to minimize (eliminate) the (probability of) load shedding during system peak load and not to accurately compute the load shedding cost.

Proposed TEP Solution

- The **Benders decomposition** approach in conjunction with **Monte Carlo (MC) simulation** is used to solve the proposed probabilistic TEP.
- Using MC, the probabilities of appearance of each one of the uncertainties are simulated through the examination of multiple probable operating scenarios.



Benders Method

The problem is divided into subproblems that are sequentially solved until the algorithm converges:

1. **Investment Problem** (Master Problem)
    - It is an integer programming problem.
    - It computes the new lines that have to be added in order the investment cost to be minimum.
2. **Probabilistic Operation** Subproblem(s)
    - It is a linear programming problem (for the DC power flow model) that uses as data the new added lines computed by the investment problem.
    - It checks if the expanded network computed by the investment problem satisfies all the power system operating constraints in each one of its probable operating conditions.

Probabilistic Operation Subproblem

The values of the random variables of wind power production, peak load, and system components that are out of service, constitute a MC scenario, i.e., a probable system state

$$Min\{W_0\} = Min\left\{ p_f \sum_k r_k \right\}$$

s.t.:

$$S^T f + g + r = d \longrightarrow \boldsymbol{\pi_i}$$

$$f_{ij} - \gamma_{ij}(n_{ij}^0 + n_{ij}^t)(\theta_i - \theta_j) = 0$$

$$|f_{ij}| \leq (n_{ij}^0 + n_{ij}^t) F_{ij,max}$$

$$0 \leq g \leq g_{max}$$

$$0 \leq r \leq d$$

$$(i,j) \in \Omega$$

Probabilistic Operation Subproblem

Calculation steps:

- Determination of lines FOR and respective uniform pdf
- Determination of peak load pdf
- Determination of Weibull functions of wind parks

- For each MC iteration:
  - Creation of random numbers from the pdf of random variables
  - Solution of the optimization problem
  - Calculation of the expected load shedding cost

- Repeat MC simulation until sufficient accuracy is obtained
- Compute the probability $Pr\{W_0 > L_{max}\}$

Investment Problem

$$Min\left\{\sum_{(i,j)} IC_{ij} n_{ij}\right\}$$

s.t.:

$$W_0^t + W_1^t + \sum_{(i,j)} \sigma_{ij}^k (n_{ij} - n_{ij}^t) \le \beta$$

$$0 \le n_{ij} \le n_{ij,max}$$

n_{ij} *is integer*

$$\beta \ge 0$$

Benders cuts

Probabilistic approach:

$$E\left(W_0^t\right) + \sum_{(i,j)} E\left(\sigma_{ij}^k\right)(n_{ij} - n_{ij}^t) \le \beta \quad , \quad k = 1,2,\ldots,t$$

Benders cuts are created in each operation subproblem only for the lines that are connected with buses with different "marginal" value

$$\sigma_{ij}^t = \sum_p (\pi_i^p - \pi_j^p)(\theta_i^p - \theta_j^p)\gamma_{ij}$$

or

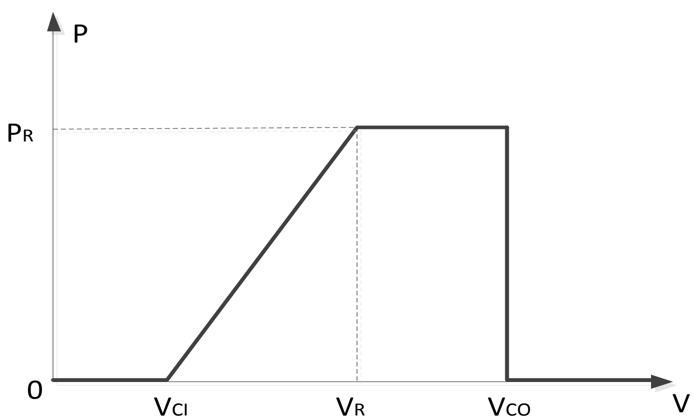
$$\sigma_{ij}^t = \sum_p (\pi_i^p - \pi_j^p) F_{ij,max}$$

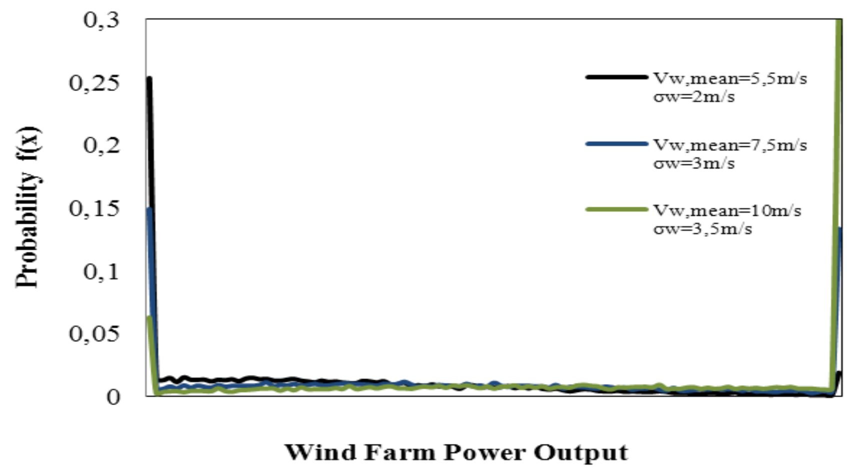
p: line contingency

Wind Power Model

- Given the mean and the standard deviation of wind speed, the Weibull function of the wind park is built:

$$k = \left(\frac{\sigma_W}{V_{W,mean}} \right)^{-1,086} \quad \text{and} \quad c = \frac{V_{W,mean}}{\Gamma\left(1 + \frac{1}{k}\right)}$$



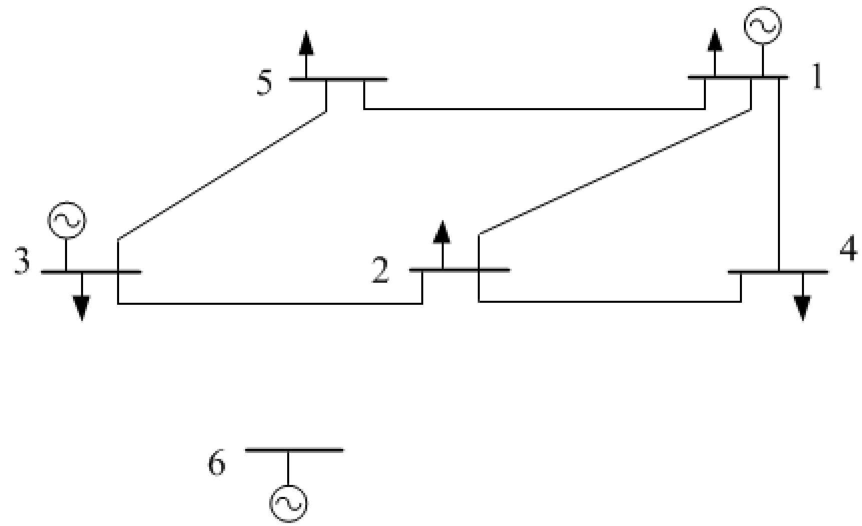


- The production from the wind park is rejected only in case an operation subproblem has no feasible solution.
- Cross-correlation index between two parks is considered.

Introduction to Results

- The method was tested on:
  - Garver 6-bus test system
  - IEEE 24-bus reliability test system
- Transmission line outages are modeled using a failure rate of 1%.
- The load penalty factor is 10^8 \$/MW.
- Up to 4 circuits per right of way could be added for Garver test system.
- Up to 3 circuits per right of way could be added for IEEE 24-bus test system.

Garver 6-Bus Test System



Garver 6-Bus Test System

- For the case of wind power production, 120 MW of conventional power was substituted by wind power at bus 3. Generation re-dispatch was implemented, with the exception of wind power.

σ_{LOAD} / E_{LOAD}	L_{max}	New lines added	Cost (k$)
0%	0%	n_{46}=3, n_{35}=2, n_{23}=1, n_{26}=1	180
	5%	n_{46}=3, n_{35}=2, n_{23}=1	150
	10%	n_{46}=3, n_{35}=1, n_{23}=1	130
5%	0%	n_{46}=3, n_{35}=2, n_{23}=2, n_{26}=1	200
	5%	n_{46}=3, n_{35}=2, n_{23}=1, n_{26}=1	180
	10%	n_{46}=3, n_{35}=2, n_{23}=1	150
10%	0%	n_{46}=3, n_{35}=2, n_{23}=1, n_{26}=2	210
	5%	n_{46}=3, n_{35}=2, n_{23}=2, n_{26}=1	200
	10%	n_{46}=3, n_{35}=2, n_{23}=1, n_{26}=1	180

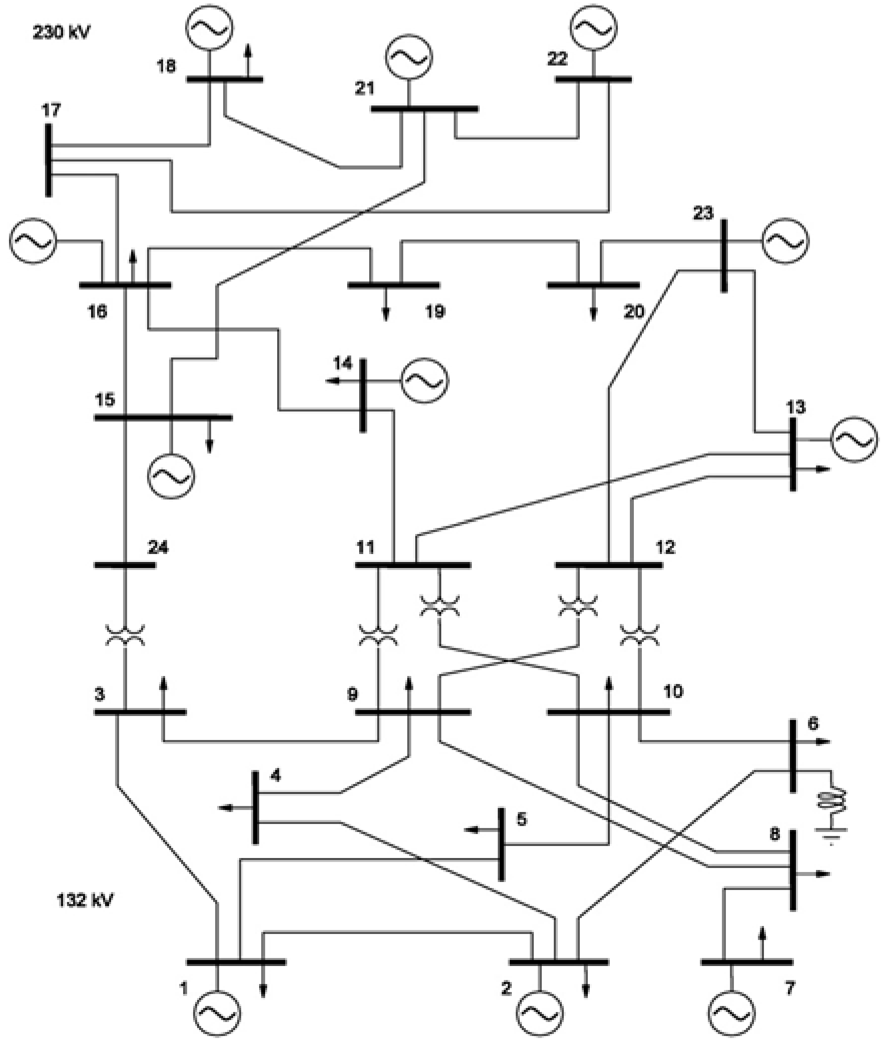
Without wind power

σ_{LOAD} / E_{LOAD} = 10%

L_{max}	New lines added	Cost (k$)
0%	n_{46}=3, n_{35}=2, n_{26}=3, n_{23}=1, n_{15}=1	260
5%	n_{46}=3, n_{35}=2, n_{26}=2, n_{23}=1, n_{15}=1	230
10%	n_{46}=3, n_{35}=2, n_{26}=2, n_{23}=1	210

New lines added	Wind characteristics	Pr{W_0>0}
n_{46}=3, n_{35}=2, n_{26}=2, n_{23}=1	$V_{w,mean}$=5,5m/s, σ_w=2m/s	0,112
	$V_{w,mean}$=7m/s, σ_w=2,5m/s	0,059
	$V_{w,mean}$=10m/s, σ_w=3,5m/s	0,031

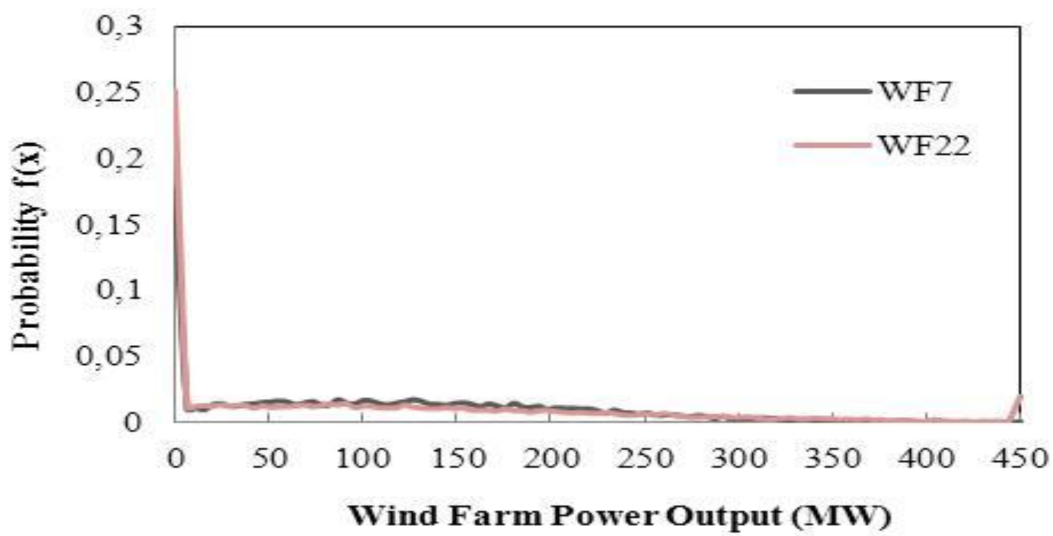
IEEE 24-Bus Test System



IEEE 24-Bus Test System

- Loads and installed generation capacity are assumed to be three times higher than their original values.

- For the case of wind power production, 450 MW of conventional power was substituted by wind power at buses 7 and 22.



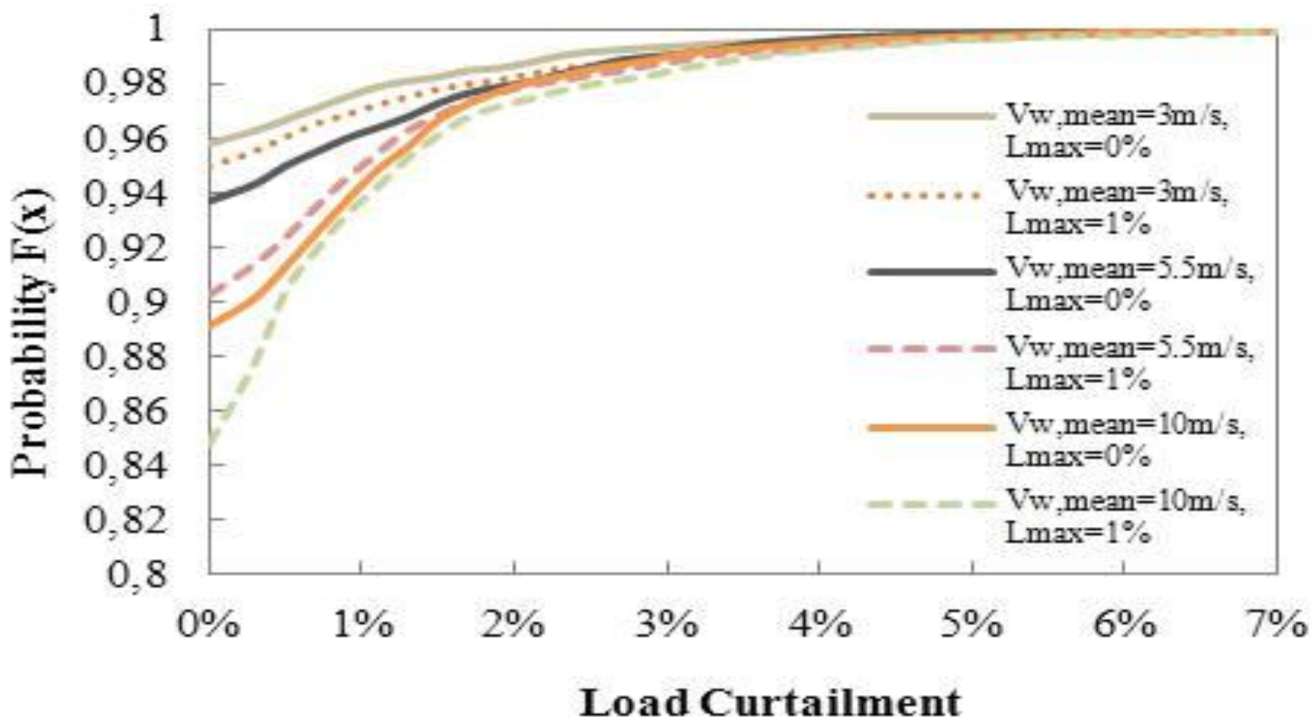
$V_{W,mean}$=5,5m/s
σ_W=2m/s
R_{xy}=0,75

Results for 5% peak load uncertainty

		Number of new lines					
		$V_{W,mean}$=3m/s, σ_W=1m/s		$V_{W,mean}$=5.5m/s, σ_W=2m/s		$V_{W,mean}$=10m/s, σ_W=3.5m/s	
From bus	To bus	L_{max}		L_{max}		L_{max}	
		0%	1%	0%	1%	0%	1%
1	5	1	1	1	1	1	1
2	4	1	1	1	1	1	
3	9	1		1			
3	24	2	2	1	1	1	1
6	10	2	2	2	2	2	2
7	8	1	1	2	2	2	2
8	9	2	2	2	1		
8	10	1				1	1
9	11	1	1	1	1		1
9	12	1	1				
10	11	1	1	1	1		
10	12	1	1	1	1	2	2
11	13	1	1	1	1		
12	13	1	1	1	1	2	1
12	23	1					
14	16	2	2	2	2	2	2
15	21	1		1			
15	24	1	1	1	1	1	1
16	17	1	2	1	2	2	1
17	18	1	2	1	1	2	1
20	23	1	1	1	1	1	1
Cost (M$)		116,3	94,3	90,2	79,6	76,6	66,1
$E(\sum r_k)$ (MW)		4,671	8,175	4,324	8,415	2,478	8,266
$\Pr\{W_0>0\}$		0,041	0,057	0,039	0,059	0,024	0,047

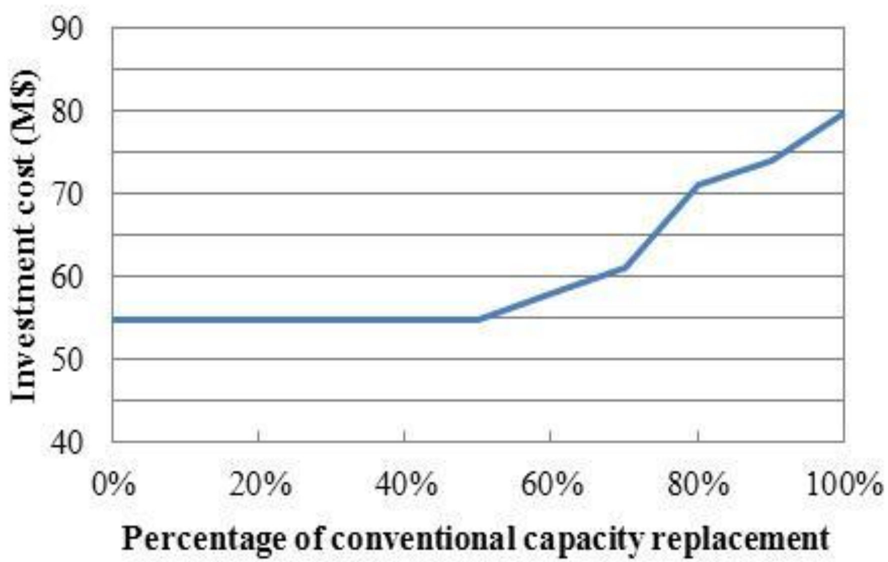
Results

➢ Cumulative distribution function, F(x), of load curtailment for zero wind power production.

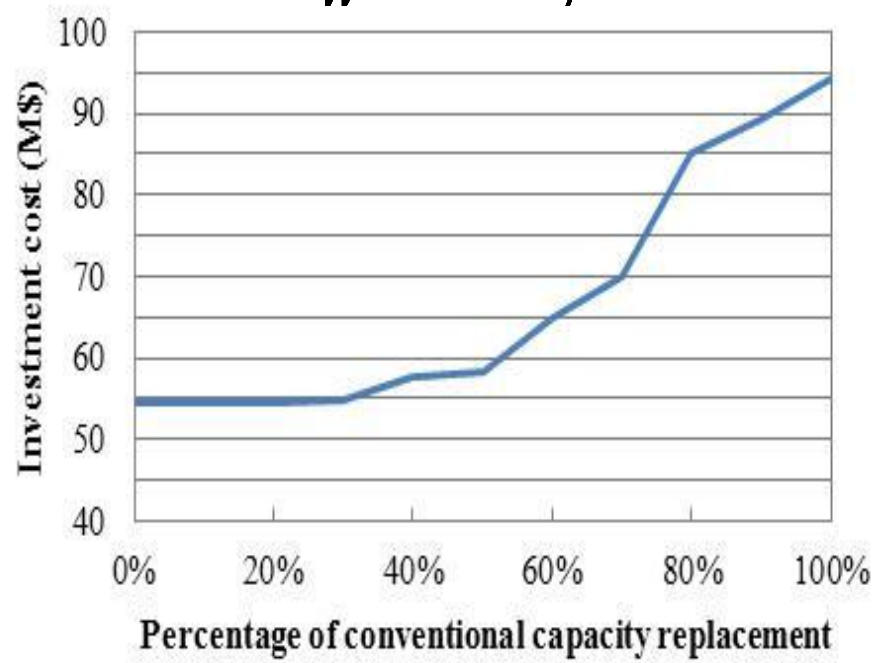


Effect of conventional capacity replacement by wind power

$$L_{max} = 1\%$$
$$\sigma_{LOAD}/E_{LOAD} = 5\%$$
$$V_{W,mean} = 5,5\ m/s$$
$$\sigma_W = 2\ m/s$$



$$L_{max} = 1\%$$
$$\sigma_{LOAD}/E_{LOAD} = 5\%$$
$$V_{W,mean} = 3\ m/s$$
$$\sigma_W = 1\ m/s$$



Conclusions

- The increase of wind power penetration into power systems has increased uncertainties and introduced new challenges to the transmission planners.
- An efficient approach to study the effect of wind power integration on transmission expansion planning was presented.
- A probabilistic framework for the TEP problem was presented that considers N-1 security analysis, as well as uncertainties in wind power generation and load demand.

Conclusions

- The Benders decomposition approach in conjunction with Monte Carlo (MC) simulation was used to solve the proposed probabilistic TEP.
- The incorporation of a variety of uncertainties increases transmission investment cost, which can be mitigated by the introduced upper limit in load shedding.
- The effect of wind integration in transmission planning is evaluated for different wind speed characteristics and for replacement of various amounts of conventional generation.

Conclusions

- Transmission investments with increased security should be decided based on a probabilistic approach that takes into consideration load demand and wind power generation uncertainties.
- The probabilistic method presented can be effectively used to provide effective transmission expansion plans with increased flexibility.

References

1. G.A. Orfanos, P.S. Georgilakis, N.D. Hatziargyriou, "Transmission expansion planning of systems with increasing wind power integration," *IEEE Transactions on Power Systems*, article in press.