

Security Region based Probabilistic Security Assessment of Power System

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Research background

integration of wind power/solar power

- Wind/solar Power's Today/Future
  - Grid integration: 26.7% by the end of 2021 in China
  - The goal: wind and solar power account for 50% of total energy by 2050 in China
- Character of wind power
  - Different dynamic characteristics
  - Intermittent and probabilistic

Probabilistic Dynamic Security Assessment (PDSA)

the basic idea and the key point

	Operating condition given configuration/network parameter	Contingency set	Assessment index
Deterministic approach	Given nodal injection	Given a set of contingencies	Secure/Insecure
Probabilistic approach	Uncertain nodal injection	Given a set of contingencies /consider their uncertainties	Probability of Security/Insecurity

Step1
Probabilistic model of uncertain factors

Load **(truncated) normal distribution**
Wind **Weibull distribution**

Type
Location
Clearing time
discrete probability model

Step2
Probabilistic index (establish/calculate)

$$\mathrm{PDS}=\sum_{i}^{N}\Pr(F_i)\cdot\Pr(\mathrm{TS}|F_i) \longrightarrow \mathrm{PDS}=\sum_{i}^{N}\Pr(F_i)\cdot\sum_{j=1}^{N_T}\Pr(A=j|F_i)\cdot\sum_{c=1}^{N_C}\xi_c[\sum_{l=1}^{N_L}\xi_l\Pr(\mathrm{TS}|F_i\cap(A=j)\cap\tau_c\cap\gamma_l]$$

PTS--probability of transient stability given some fault

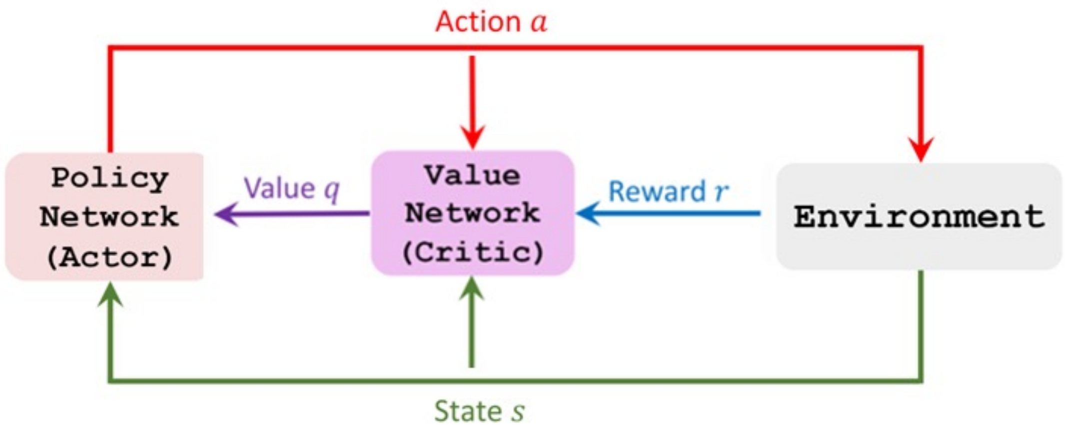
- **calculating PTS is the most fundamental and critical part**
- **the number of fault scenarios is $N\times N_T\times N_C\times N_L$, same number of PTS is required to calculate**
- **PTS is the extraordinary complicated n-degree integral in n-dimension power injection space**
- **Monte Carlo is usually used with huge computation burden**
- **An efficient method for calculating PTS analytically is the key**

Probabilistic Dynamic Security Assessment (PDSA)

probabilistic modelling of wind power

- Reinforcement learning (RL) based probabilistic forecasting

■ Utilizing the **self-optimization capability** of RL to improve learning ability of system in the process of continuous **interaction with the environment**, thus obtaining more accurate forecasting results.



RL based probabilistic modelling

$$\max_{\theta_1,\ldots,\theta_H} E_\pi\left[\boxed{\sum_{k=0}^{\infty}\gamma^k r_{n+k+1}^h}\,\middle|\, s_n = s\right]$$

Value network

$$s.t.\begin{cases} 0 \le \boxed{\pi^h\left(a_n | s_n, \boldsymbol{\theta}\right)} \le 1 \quad \forall h, n \\ \pi^h\left(a_n | s_n, \boldsymbol{\theta}\right) \le \pi^{h+1}\boxed{\left(a_n | s_n,\right.}\left.\boldsymbol{\theta}\right) \quad 1 \le h \le H\text{-}1 \\ \boxed{r_n} = -1 \times \max\begin{cases} \varphi_h(y_n - a_n) \\ (\varphi_h - 1)(y_n - a_n) \end{cases} \end{cases}$$

Policy network

Historical & predicted value

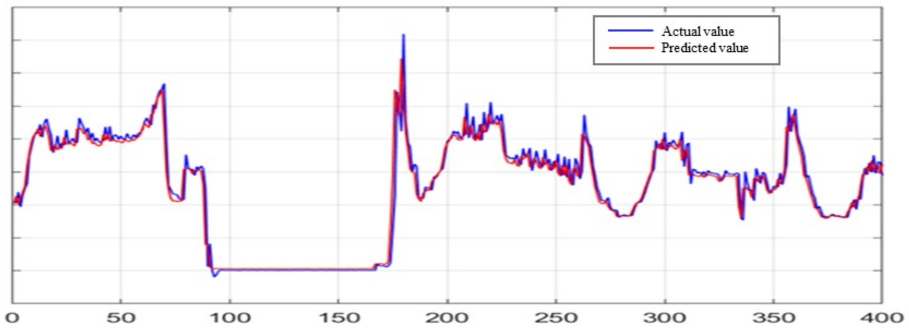
Reward

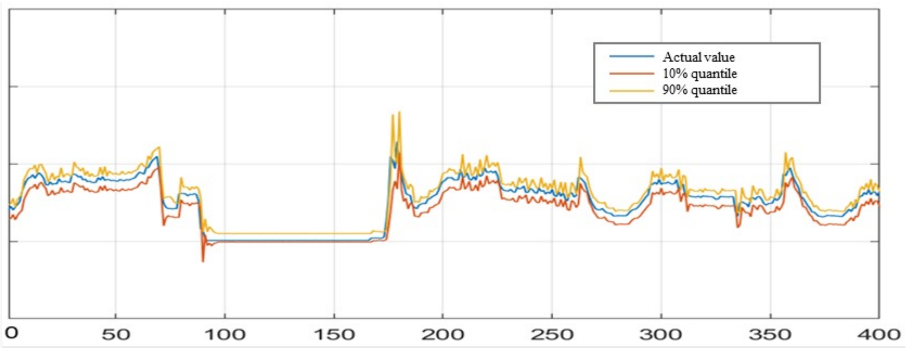
Probabilistic Dynamic Security Assessment (PDSA)

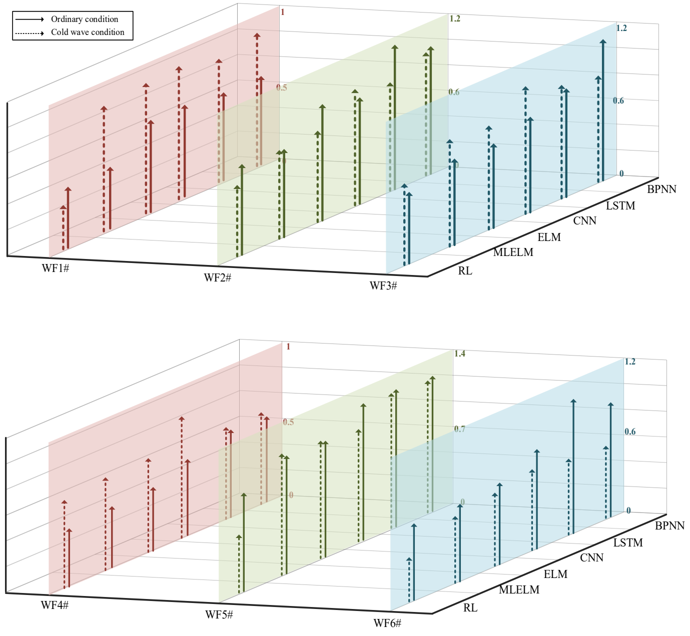
probabilistic modelling of wind power

Probabilistic model outperforms deterministic model to describe wind power uncertainty

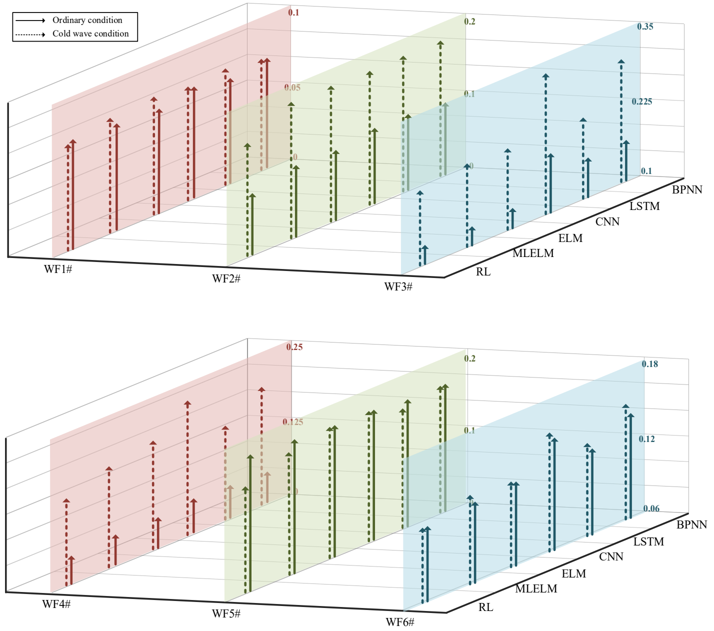
RL provides better probabilistic regression results than other methods under different conditions







Reliability



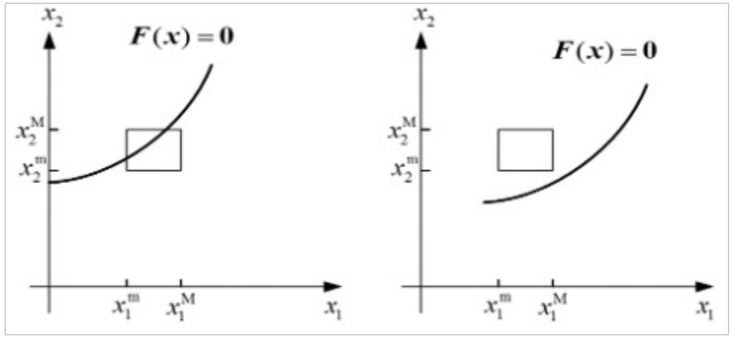
Skill score

Probabilistic Dynamic Security Assessment (PDSA)

PTS based on practical dynamic security region(PDSR)

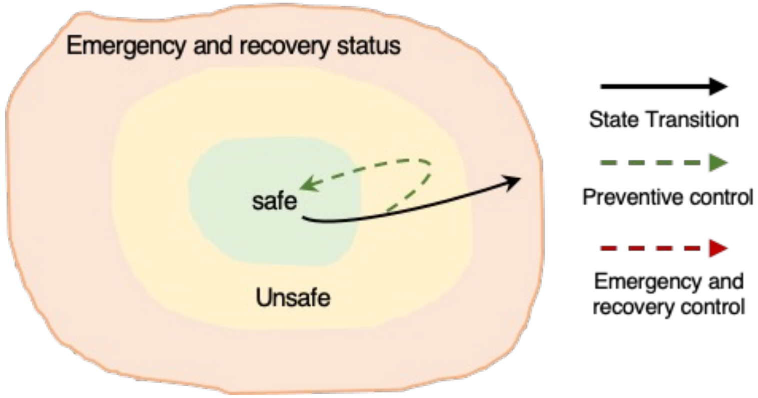
Point-wise Method:
Check whether the OP satisfies the power flow constraints by numerical calculations.

Security Region Methodology:
Defined a region in the decision space that all OPs inside can guarantee safety.



(a) With solution satisfying security constraints

(b)Without solution satisfying security constraints



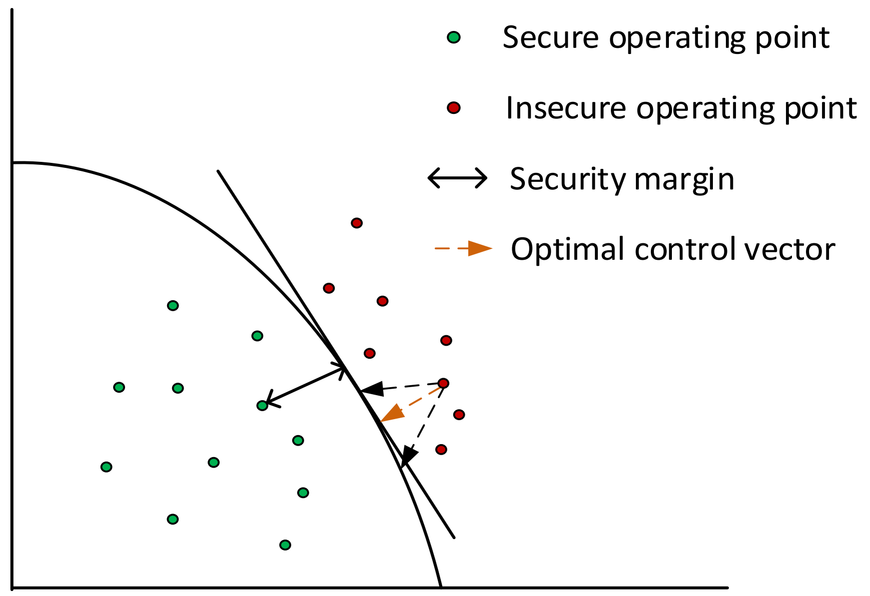
Probabilistic Dynamic Security Assessment (PDSA)

PTS based on practical dynamic security region(PDSR)

- Practical Dynamic Security Region(PDSR)

Within the acceptable range of engineering application, the boundary of PDSR of a power system with double fed induction generator (DFIG) can be approximated by one or a few hyper-planes in power injection space

$$\Omega_d := \left\{ \boldsymbol{P} \in \mathbf{R}^n \;\middle|\; \begin{array}{c} \sum_{i=1}^{n} \alpha_i P_i \le 1 \\ P_i^m \le P_i \le P_i^M, i = 1, 2, \ldots, n \end{array} \right\}$$



- To given P and (i, j, F), whether system is transient stable can be judged by comparing $\sum \alpha_i P_i$ and 1, in other words, transient stability criteria is analytically expressed by the linear combination of nodal injection power.
- To given (i, j, F), , PDSR is determined and unrelated with nodal injection power and thus α_i can be calculated offline and used online.

Probabilistic Dynamic Security Assessment (PDSA)

PTS based on practical dynamic security region(PDSR)

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PTS based on PDSR

$$\begin{aligned} \text{PTS} &= \Pr\{\boldsymbol{y} \in \Omega_d(i, j, F)\} \\ &= \Pr\{\sum_{i}^{n} \alpha_i P_i \le 1\} \\ &= \int_{y^e < 0} g(y^e) dy^e = 1 - G(y^e) \end{aligned}$$

- ➢ To given *P* and (*i*, *j*, *F*), whether system is transient stable can be judged by comparing $\sum \alpha_i P_i$ and 1, in other words, transient stability criteria is analytically expressed by the linear combination of nodal injection power.
- ➢ To given (*i*, *j*, *F*), , PDSR is determined and unrelated with nodal injection power and thus α_i can be calculated offline and used online.

Probabilistic Dynamic Security Assessment (PDSA)

effective method to calculate PTS based on PDSR

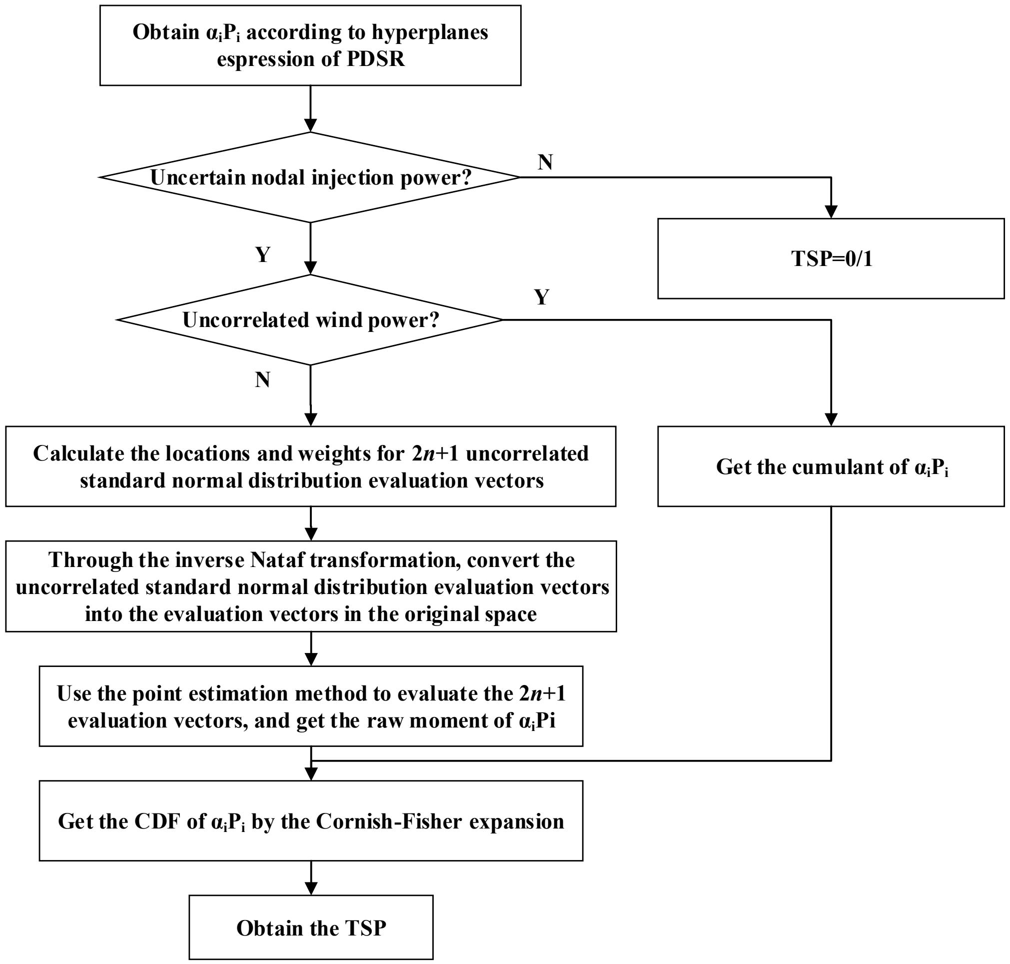
- Analytical method to calculate PTS

$$
\begin{aligned}
\text{PTS} &= \Pr\{\boldsymbol{y} \in \Omega_d(i, j, F)\} \\
&= \Pr\{\sum_i^n \alpha_i P_i \le 1\} \\
&= \int_{y^e<0} \underline{\underline{g(y^e)}}dy^e = 1 - G(y^e)
\end{aligned}
$$

Considering the input random variables are non-Gaussian

—combined cumulants and Cornish-Fisher expansion is applied

—ignoring the correlation



Probabilistic Dynamic Security Assessment (PDSA)

effective method to calculate PTS based on PDSR

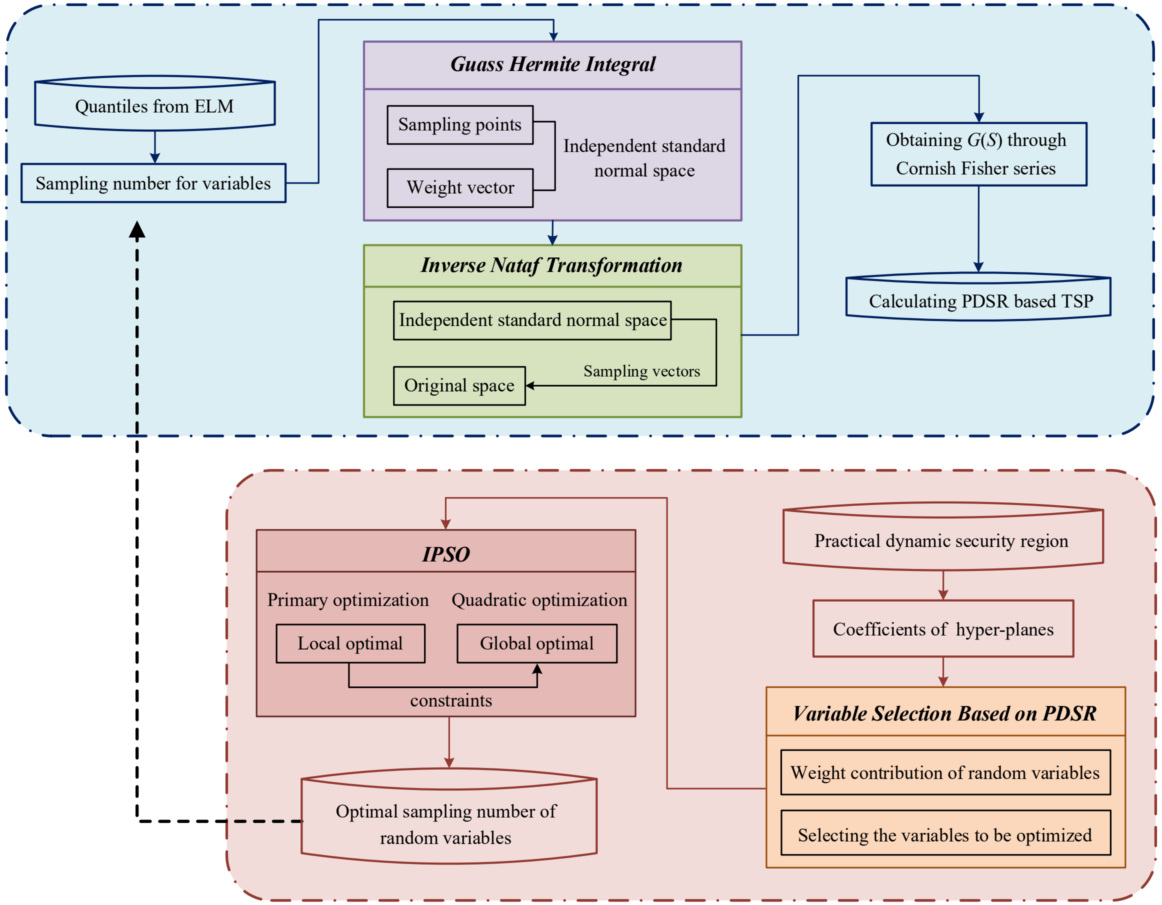
- Analytical method to calculate PTS

$$\begin{aligned}\text{PTS} &= \Pr\{\boldsymbol{y} \in \Omega_d(i,j,F)\} \\ &= \Pr\{\sum_{i}^{n} \alpha_i P_i \le 1\} \\ &= \int_{y^e<0} g(y^e)dy^e = 1 - G(y^e)\end{aligned}$$

Considering the input random variables are non-Gaussian

—Gauss-Hermite integral based improved point estimation method is applied

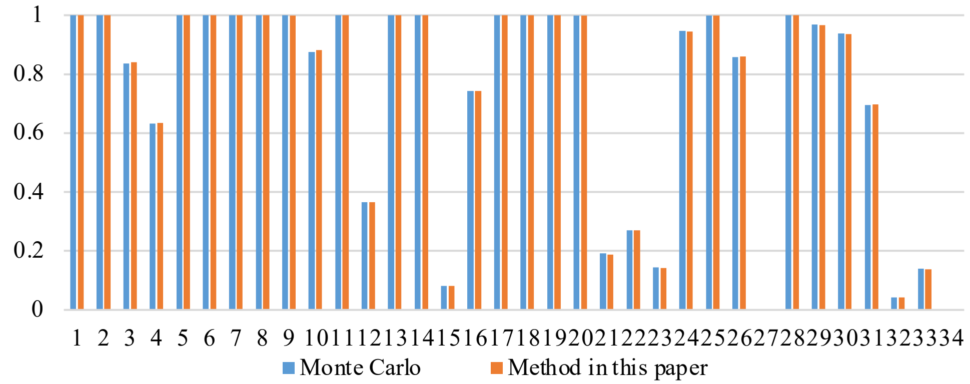
—considering the correlation of wind power



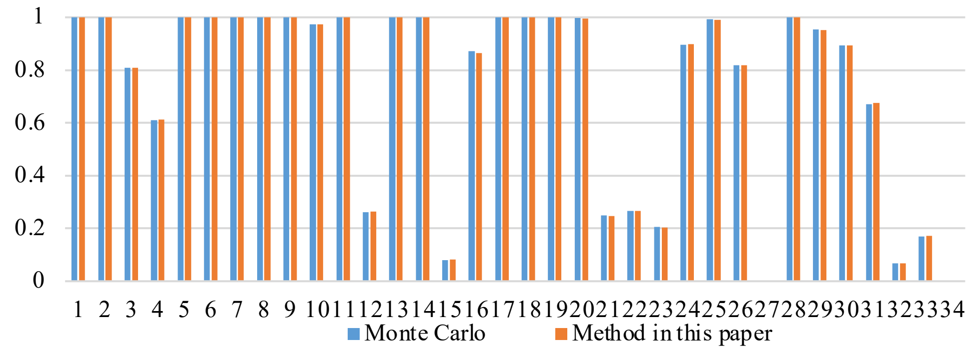
Probabilistic Dynamic Security Assessment (PDSA)

case study

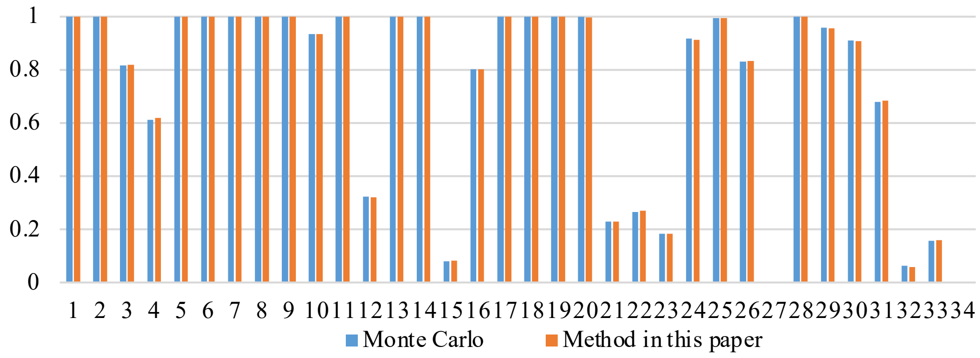
correlation coefficient=0, max error=2.47%



correlation coefficient=0.8, max error=1.24%



correlation coefficient=0.5, max error=3.29%



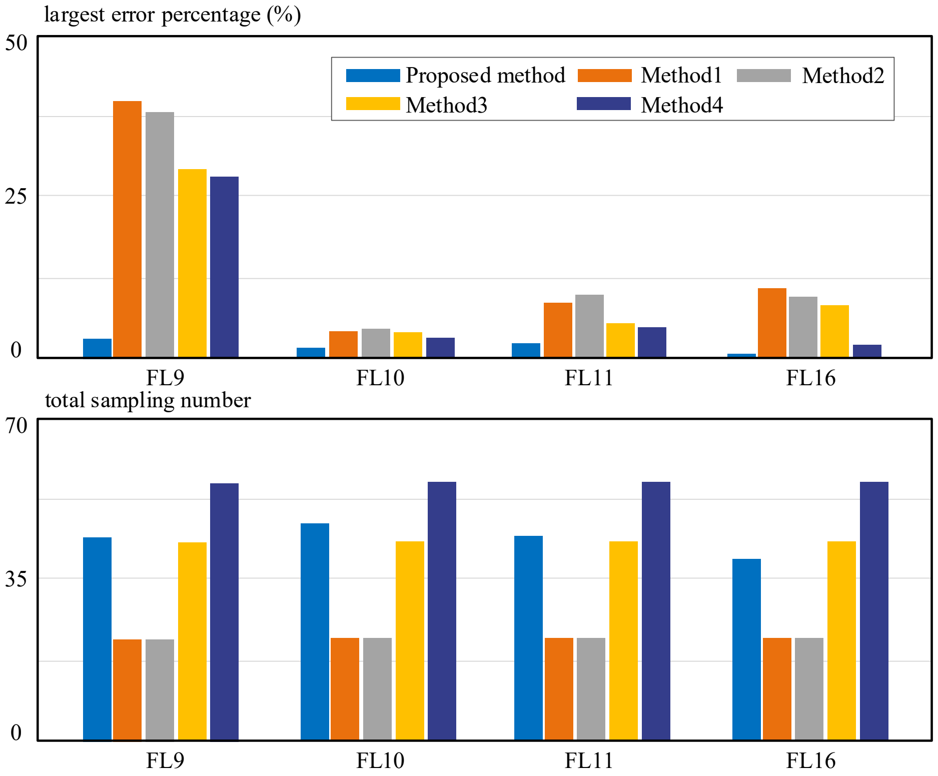
Much faster computing speed

	Method in this paper	Monte Carlo
0	1.248562s	150.9823s
0.5	1.709441s	115.8295s
0.8	1.835562s	126.0477s

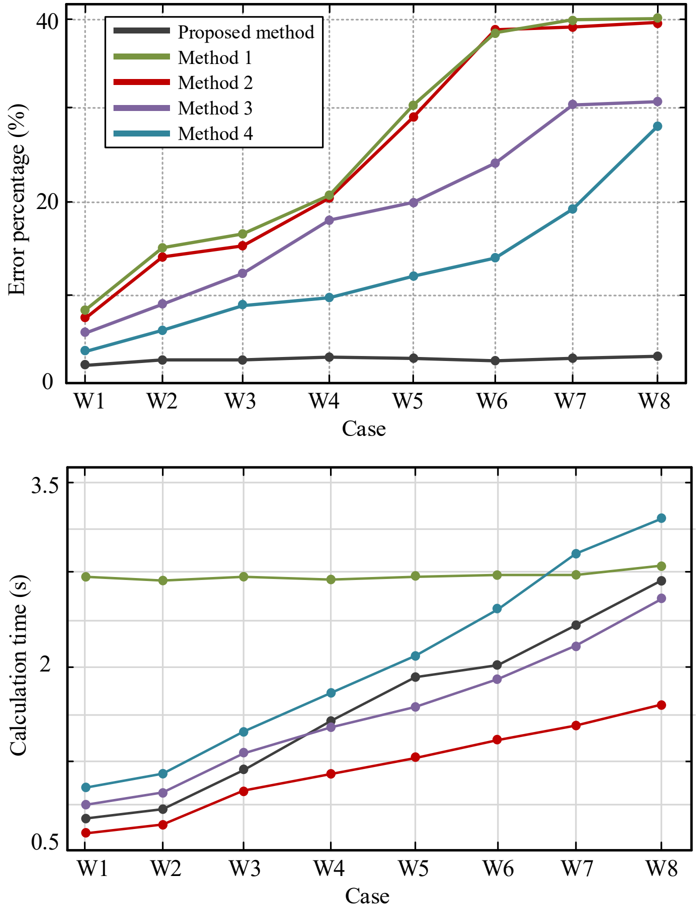
Probabilistic Dynamic Security Assessment (PDSA)

case study

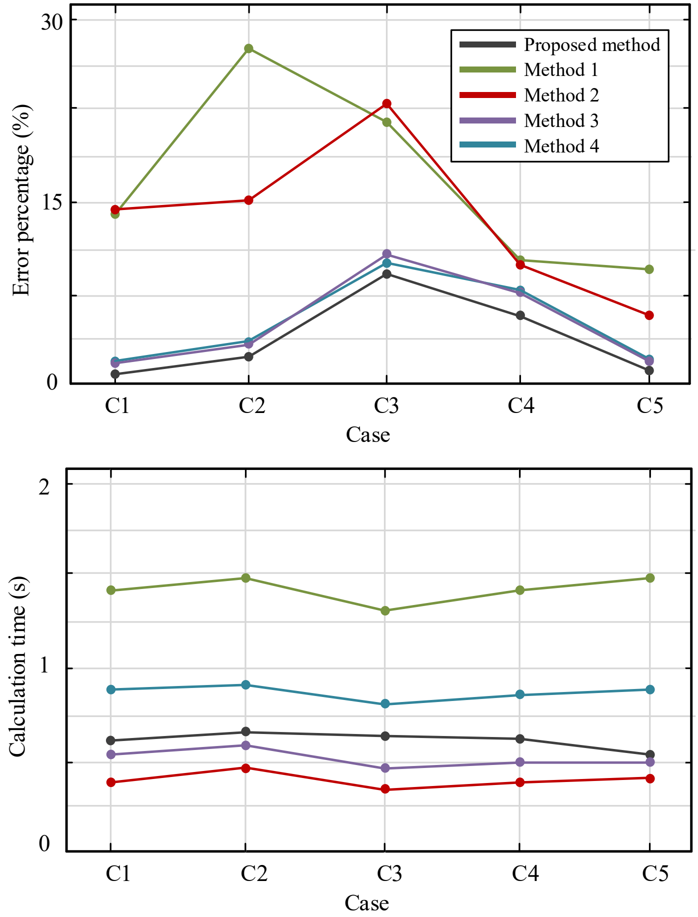
Higher assessment accuracy without much loss of computational efficiency



Correlation coefficient=0.8 , maximal penetration level



Fixed correlation, different penetration levels

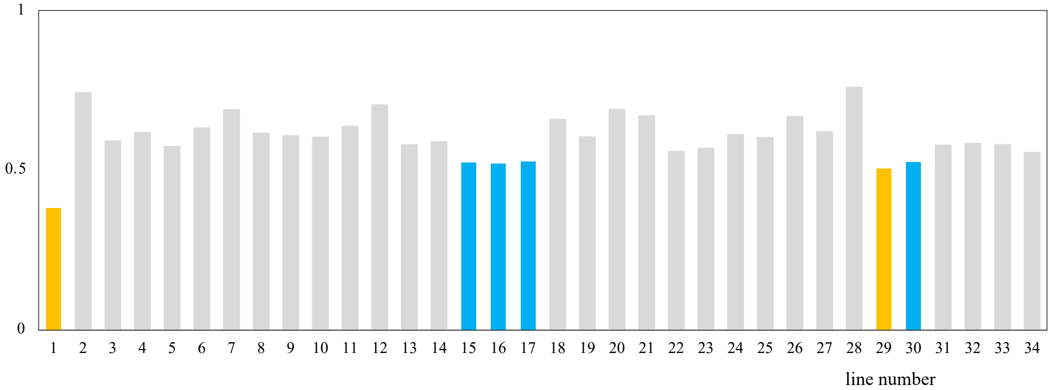


Fixed penetration, different correlation levels

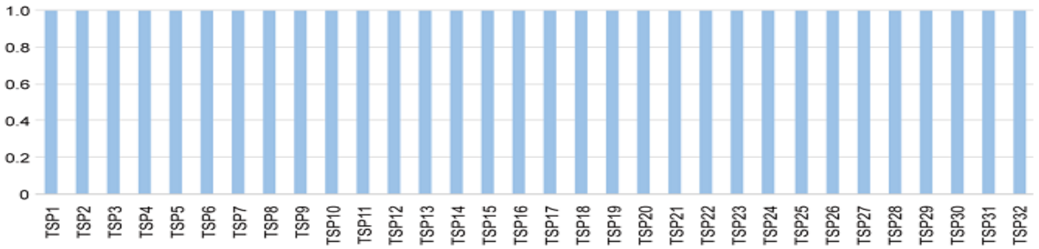
Probabilistic Dynamic Security Assessment (PDSA)

case study

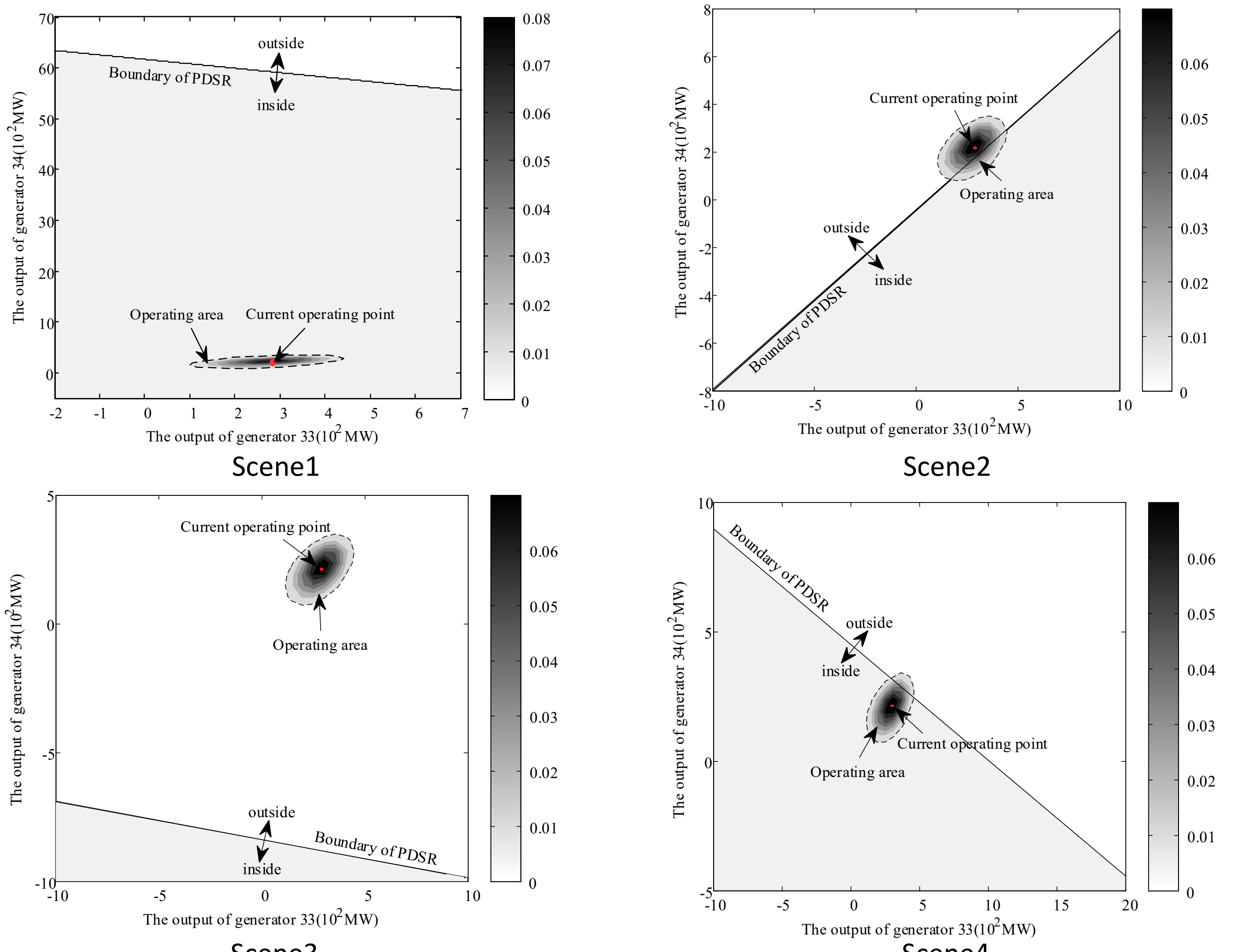
Probabilistic approach can further reveal the stable degree and provide the line that requires more attention



PTS corresponding to N-1 fault on each line at t=12h



Deterministic assessment of N-1 fault at t=12h



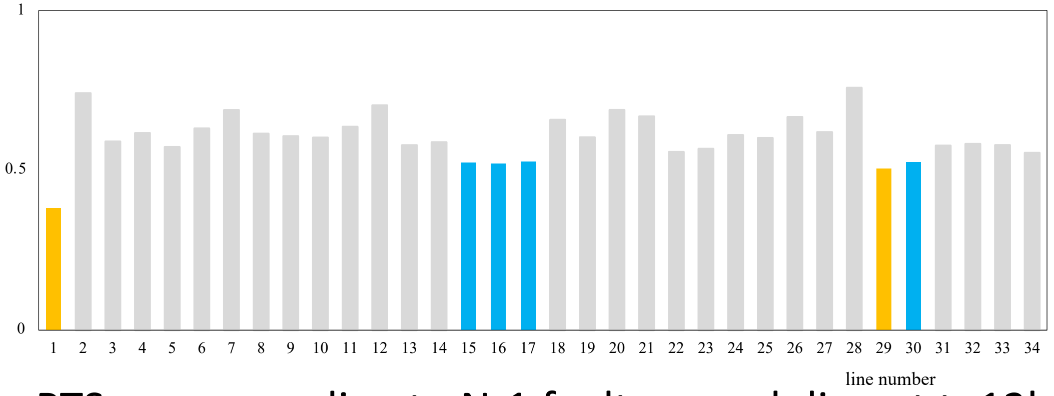
Scene1 Scene2 Scene3 Scene4

Probabilistic Dynamic Security Assessment (PDSA)

case study

Probabilistic approach can further reveal the stable degree and provide the line that requires more attention

The highest error is 1.16% and reveal future security level



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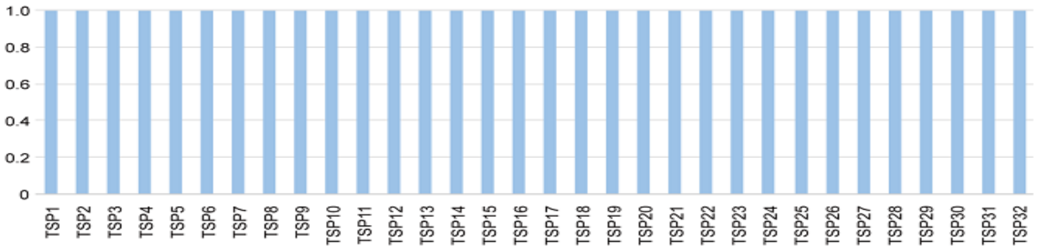

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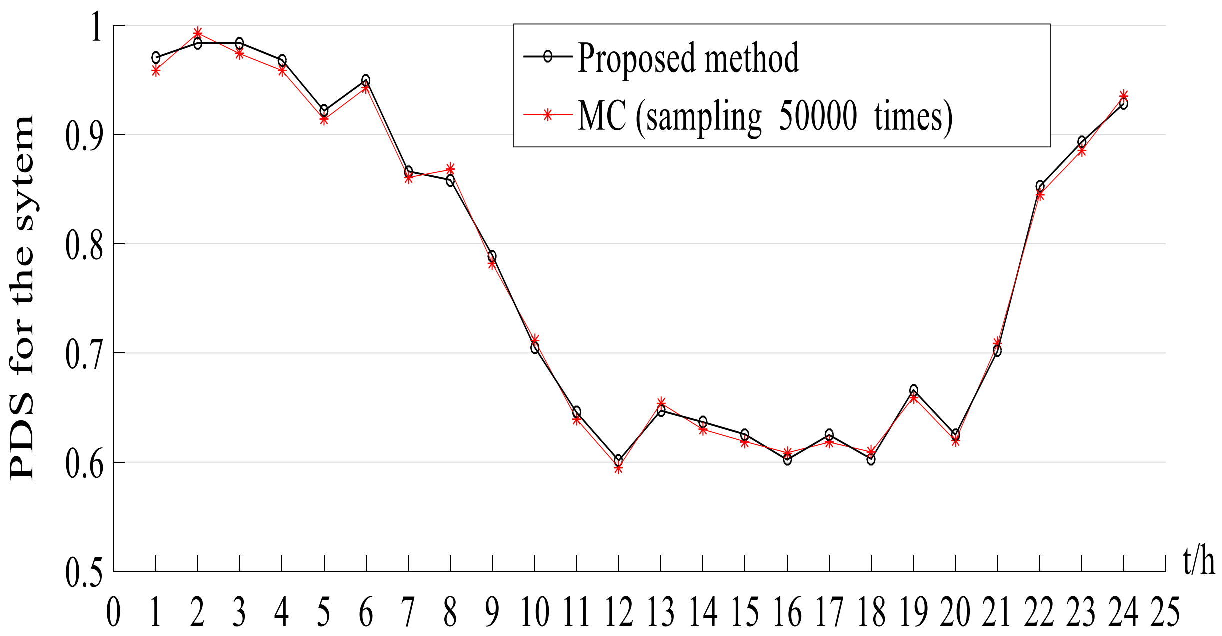


Probabilistic Dynamic Security Assessment (PDSA)

feasibility analysis on the approach's application in large-scale power system

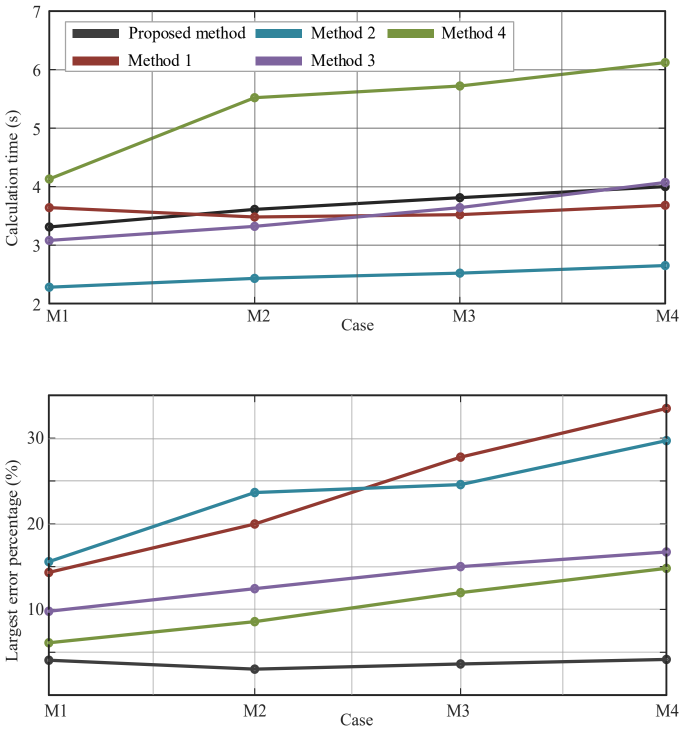
- Applied in some practical provincial grid of china, which includes 1017 buses and 1072 branches

Higher assessment accuracy without much loss of computational efficiency

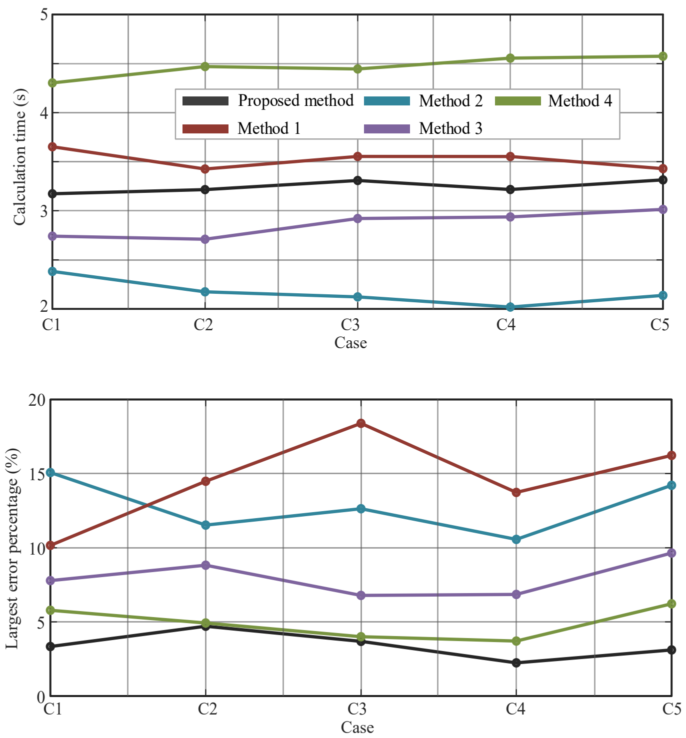
☐ DSR is obtained in seventeen critical nodal injection space including all voltage level.

☐ The fault list includes 3 critical N-1 fault according to practical operation experience.

☐ Different wind farms are integrated.



Fixed correlation, different penetration levels



Fixed penetration, different correlation levels

Probabilistic Dynamic Security Assessment (PDSA)

feasibility analysis on the approach's application in large-scale power system

- The computing time of the proposed approach in different system is estimated on one same computer

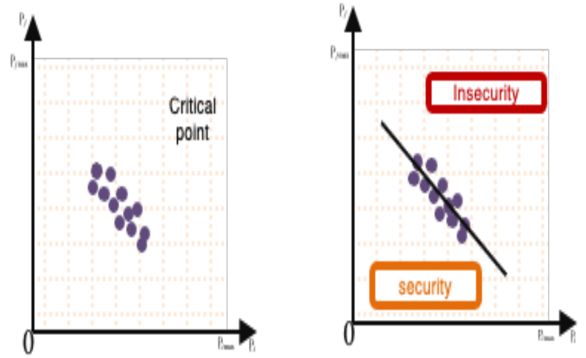
Estimated System	Number of fault / fault scenarios	Computing time on one PC (s)
IEEE118 Bus System	186/10044	7.39
IEEE145 Bus System	453/24462	18.43
Practical Provincial Grid of China	1072/57888	42.49

- ✓ Fault list includes all N-1 three-phase short-circuit fault on line, each fault has 54 scenarios
- ✓ DSR is obtained in critical nodal injection space and there are no more than 30 critical nodes
- ✓ Lenovo computer with Intel Core i5-3230M CPU @2.6GHz, 4G RAM

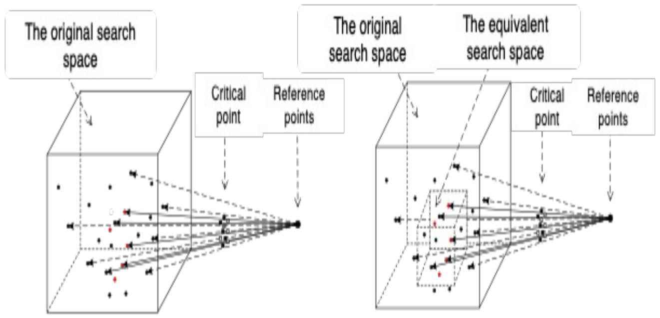
The computing time almost increases linearly. The time for each system is no more than 1 minute.

Probabilistic Dynamic Security Assessment (PDSA)

Hybrid data driven method for PDSR

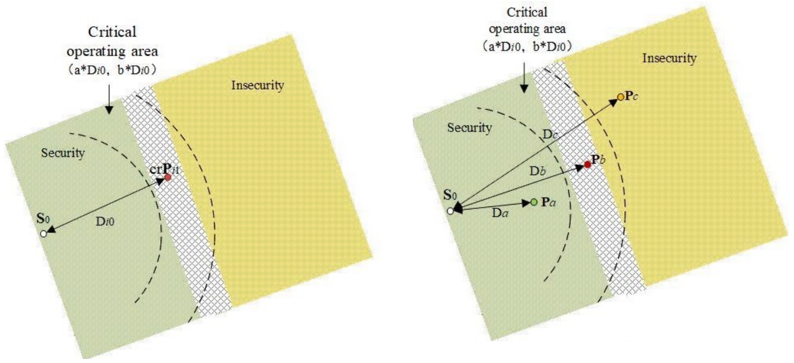


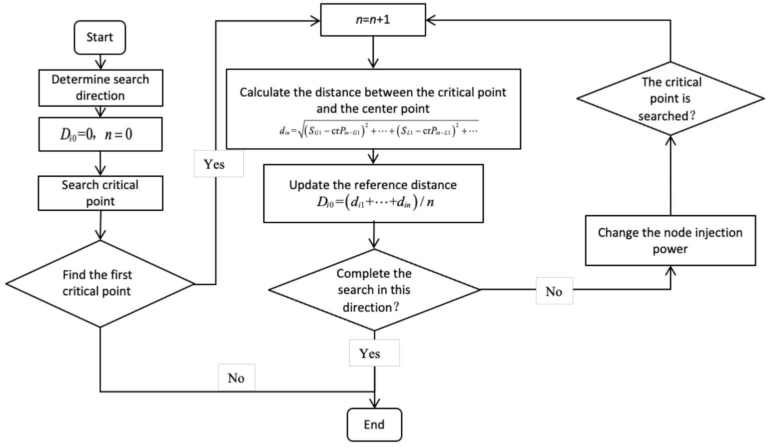
Schematic diagrams of approximating boundary in two-dimension space



Original search space and equivalent search space in three-dimensional space

Space division (locate critical operating area)



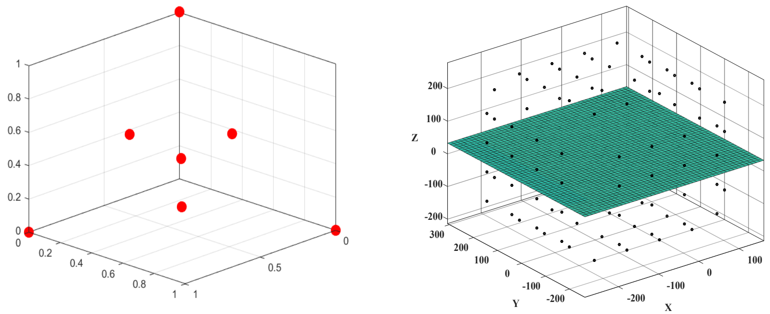


Equivalent search space construction

RELIEF algorithm is applied to identify the key generators; then, the equivalent search space is determined by using the orthogonal point selection method and identified key generators.

$$W[X]^{i+1} = W[X]^{i} - \frac{\boxed{diff(X, R_i, R_{nh})}}{m} + \frac{\boxed{diff(X, R_i, R_{nm})}}{m}, \quad i \le m$$

$$\boxed{diff(X, A, B) = \frac{|value(X, A) - value(X, B)|}{\max(X) - \min(X)}}$$



Probabilistic Dynamic Security Assessment (PDSA)

Hybrid data driven method for PDSR

Efficiency of Hybrid data-driven method (only RELIEF used)

Maximum fitting error	Fitting	Hybrid data-driven method
Case 1	6.70e-05	1.21e-16
Case 2	1.67e-04	4.99e-16
Case 3	4.59e-04	1.55e-16

Time cost/s	Fitting	Hybrid data-driven method
Case 1	1569.32	963.74
Case 2	1644.42	922.21
Case 3	3642.05	1756.72

Fault line	Fitting			Hybrid data-driven method				Time reduced %
	Time cost	Number of CP	Max error	Critical Gen	Time cost	Number of CP	Max error	
1-2	1563.47	34	3.0150e-05	1/2/9	1016.86	34	2.4441e-16	34.96%
1-39	1569.32	34	6.7010e-05	1/2/8	963.74	33	1.2133e-16	38.59%
2-25	1955.77	53	2.4908e-04	3/5/6	932.97	32	2.8108e-16	52.30%
3-4	1504.27	35	7.5639e-05	4/5/7	960.25	35	1.6410e-16	36.17%
3-18	1464.71	34	9.7058e-05	1/6/8	920.69	32	5.9043e-16	37.14%
8-9	1830.09	34	1.0488e-18	1/6/9	898.45	29	9.2996e-17	50.91%
9-39	2385.47	58	1.5607e-18	1/6/9	780.54	23	1.3439e-16	67.28%
14-15	1371.14	29	4.4274e-07	1/2/7	902.41	28	5.8702e-18	34.19%
15-16	1520.60	29	2.2013e-05	1/2/7	776.37	28	1.4363e-13	48.94%
16-17	1636.63	33	7.6601e-05	1/7/9	897.99	30	2.0230e-12	45.13%
16-21	1683.77	38	1.4417e-04	1/2/7	875.63	28	1.3427e-17	48.00%
16-24	1652.28	34	8.3072e-05	1/2/7	775.80	29	8.3967e-17	53.05%
17-18	1657.06	32	3.5499e-05	1/2/7	814.90	28	9.1346e-18	50.82%
17-27	2275.00	52	2.6552e-04	6/7/8	1046.78	35	1.7326e-16	53.99%
21-22	1765.41	41	2.7603e-04	4/5/6	813.94	28	2.7281e-18	53.90%
22-23	2530.98	70	1.5724e-18	1/2/9	974.37	34	1.0184e-16	61.50%
23-24	1660.66	34	1.6357e-04	1/2/6	841.67	29	2.3088e-16	49.32%
25-26	1644.42	36	1.6674e-04	1/7/8	922.21	33	4.9930e-16	43.92%
26-27	1602.69	35	6.8009e-05	6/7/8	876.89	30	2.1450e-16	45.29%
26-28	3642.05	44	4.5950e-04	2/7/8	1756.72	32	1.5502e-16	51.77%
		48	4.8978e-17			32	9.7309e-17	
26-29	1541.81	32	5.1383e-04	1/2/8	880.20	34	1.5793e-16	42.91%
28-29	5138.30	50	3.0150e-05	2/4/8	1823.24	30	2.4441e-16	64.52%
		63	6.7010e-05			28	1.2133e-16	

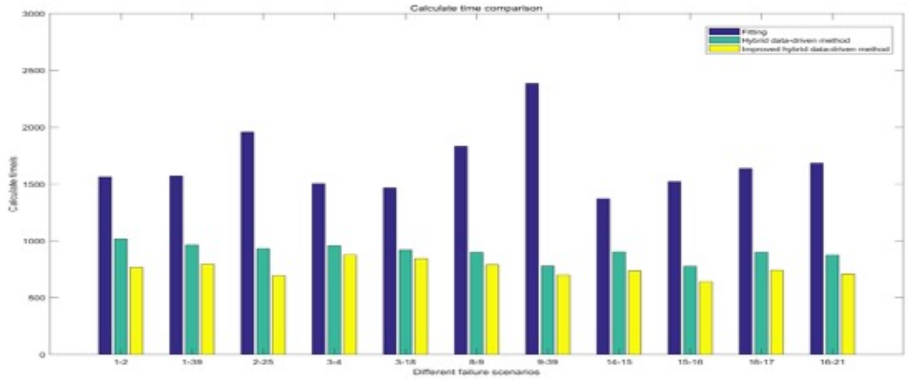
Computational efficiency of the proposed method is much higher than the commonly used fitting method without the loss of accuracy. (calculation time is reduced by 48.39% on average)

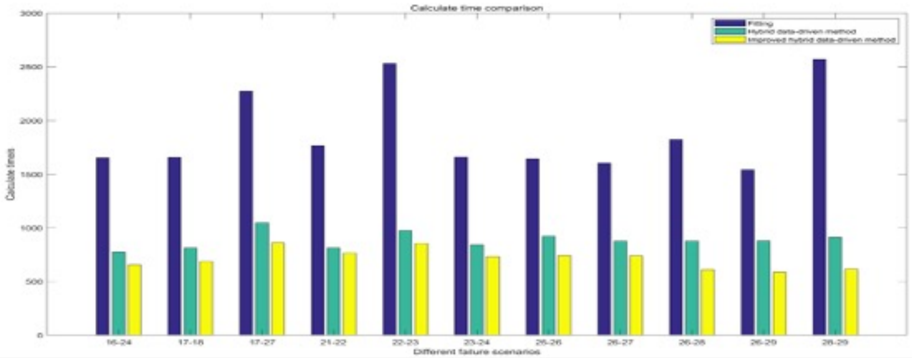
Probabilistic Dynamic Security Assessment (PDSA)

Hybrid data driven method for PDSR

Efficiency of Hybrid data-driven method (space division is further used)

Fault line	Key generator number	Hybrid data-driven		Improved hybrid data-driven		Reduced time%
		Time cost/s	Number of critical points	Time cost/s	Number of critical points	
1-2	1/2/9	1016.86	34	766.84	34	24.59%
1-39	1/2/8	963.74	33	793.52	33	17.66%
2-25	3/5/6	932.97	32	693.96	32	25.62%
3-4	4/5/7	960.25	35	877.82	35	8.58%
3-18	1/6/8	920.69	32	841.55	33	8.60%
8-9	1/6/9	898.45	29	789.63	29	12.11%
9-39	1/6/9	780.54	23	700.92	23	10.20%
14-15	1/2/7	902.41	28	734.59	28	18.60%
15-16	1/2/7	776.37	28	639.07	28	17.68%
16-17	1/7/9	897.99	30	738.99	30	17.71%
16-21	1/2/7	875.63	28	707.93	28	19.15%
16-24	1/2/7	775.80	29	655.65	29	15.49%
17-18	1/2/7	814.90	28	686.57	28	15.75%
17-27	6/7/8	1046.78	35	861.35	34	17.71%
21-22	4/5/6	813.94	28	765.92	28	5.90%
22-23	1/2/9	974.37	34	854.02	34	12.35%
23-24	1/2/6	841.67	29	731.09	29	13.14%
25-26	1/7/8	922.21	33	743.15	33	19.42%
26-27	6/7/8	876.89	30	739.89	31	15.62%
26-28	2/7/8	1756.72	32 32	1217.04	33 32	30.72%
26-29	1/2/8	880.20	34	587.31	34	33.28%
28-29	2/4/8	1823.24	30 28	1227.5	31 28	32.67%





- ➢ The same critical points and corresponding boundaries can be obtained.
- ➢ The calculation time is reduced by 17.84% on average, and the total calculation time of more than 90% fault lines is less than 15min.
- ➢ Compared with the fitting method, the computation time of the improved hybrid data-driven method is reduced by 57.59% on average.

Conclusion & Future work

data-driven method works with model-based method

- It is an effective analytical approach with high accuracy and obvious advantage in computing speed
- The results of PDSA can further help operators and planners understand the security level and locate critical components
- The characteristic of PDSR makes the approach has obvious advantage and good practical application prospect.
- Data-driven method's application in PDSR and forecast of nodal injection power is our ongoing work

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