Reliability Evaluation of Renewable Generation Integrated Power Grid Including Adequacy and Dynamic Security Assessment

Vijay Vittal, ASU

Chanan Singh, TAMU

Mojdeh Khorsand, ASU

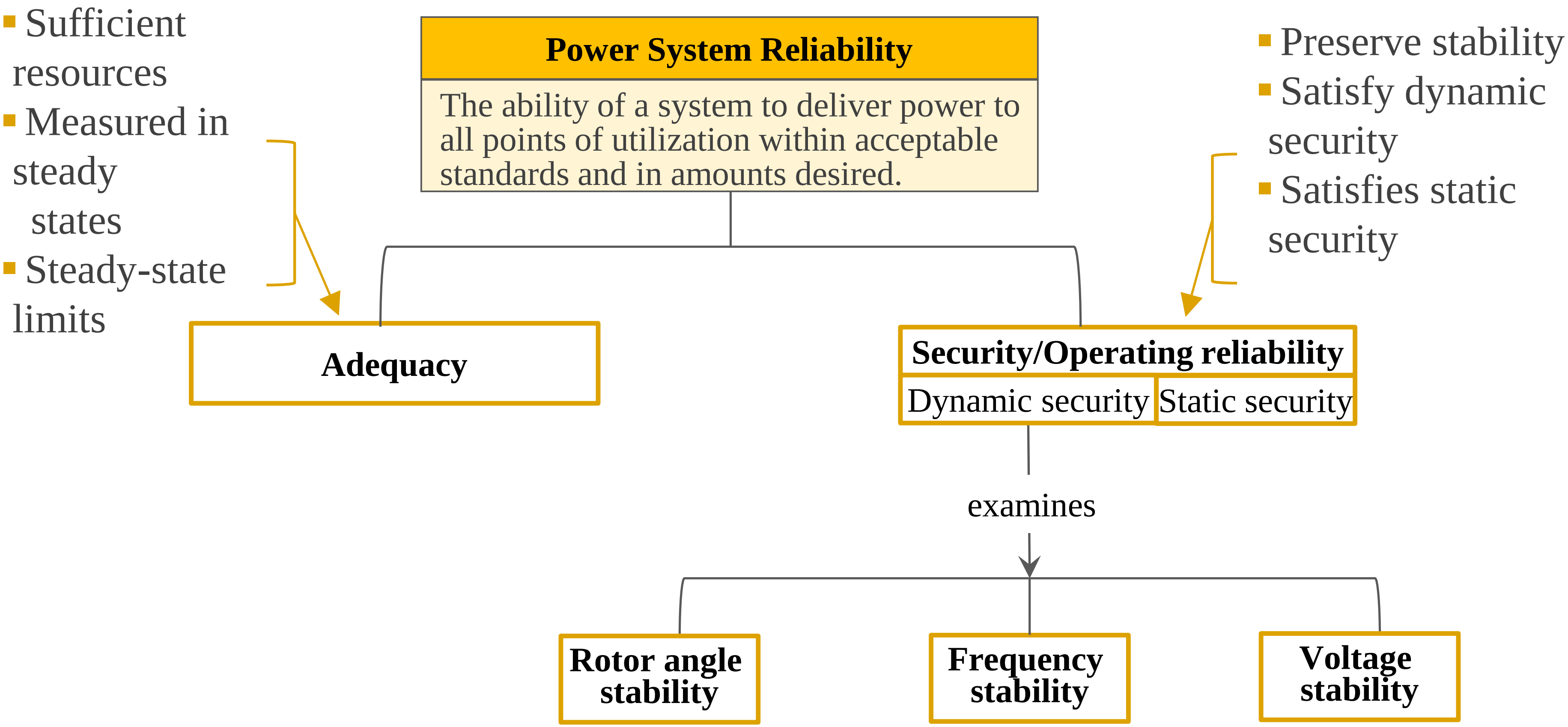
Graduate Student – Yingying Wang

PSERC Webinar
Jan 28, 2020

PSERC Project S75

- This webinar details the work done at ASU as a part of PSERC project S75
- This project was done in collaboration with Profs. Chanan Singh and Mojdeh Khorsand
- The student at ASU was Ms. Yinying Wang

Background



- Sufficient resources
- Measured in steady states
- Steady-state limits

Power System Reliability

The ability of a system to deliver power to all points of utilization within acceptable standards and in amounts desired.

Adequacy

Security/Operating reliability

Dynamic security | Static security

- Preserve stability
- Satisfy dynamic security
- Satisfies static security

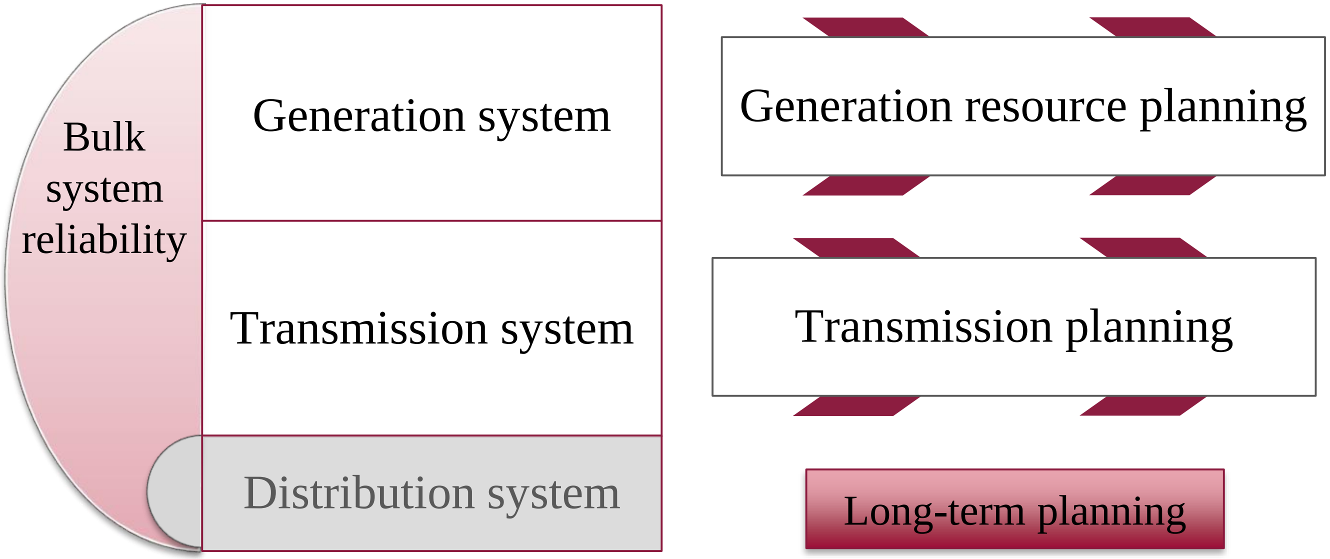
examines

Rotor angle stability

Frequency stability

Voltage stability

Background



Bulk system reliability

Generation system

Transmission system

Distribution system

Generation resource planning

Transmission planning

Long-term planning

- **Resource adequacy**
- Deterministic approaches
  - e.g. *reserve margin*
- Probabilistic approaches
  - e.g. *LOLE*, *LOLP*

- **Security**
- Deterministic approaches
  - e.g. *N-1 criteria*

Current practice

Can the present approaches meet the need in the transforming power systems ?

Objectives

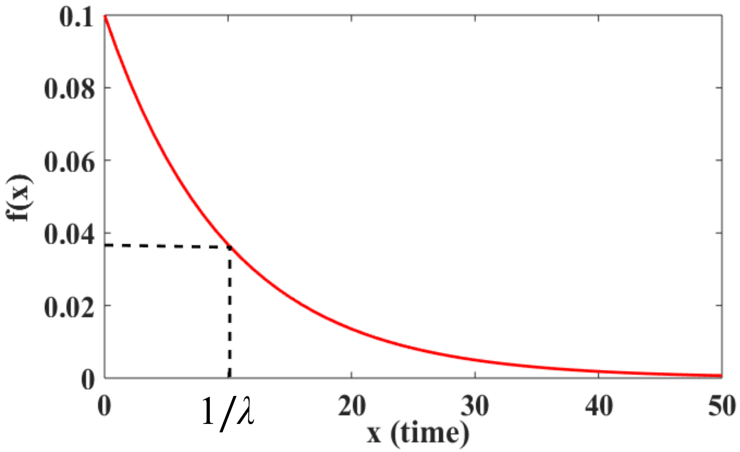
- Develop a probabilistic reliability evaluation approach for the composite system
- Integrate adequacy assessment and dynamic security assessment into a single framework based on probabilistic analysis methodology
- Represent stochastic characteristics and dynamic behavior of renewable energy resources in the integrated evaluation
- Provide methods to improve computational efficiency

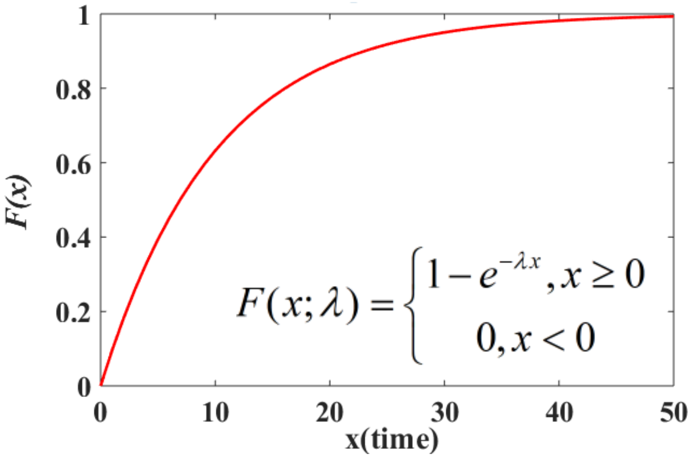
Probabilistic analysis methods

- Analytical methods
  - Such as the state enumeration method
  - Suitable for systems with small failure rate
  - Also suitable for systems that have simple operating conditions
- Monte Carlo simulation
  - Non-sequential (random sampling)
  - Time sequential

Methods of probabilistic analysis

- Sequential Monte Carlo simulation
  - Based on sampling a probability distribution of component state durations
  - The distribution assumed for up and down times are exponential
  - The distribution parameter is the failure/ repair rate

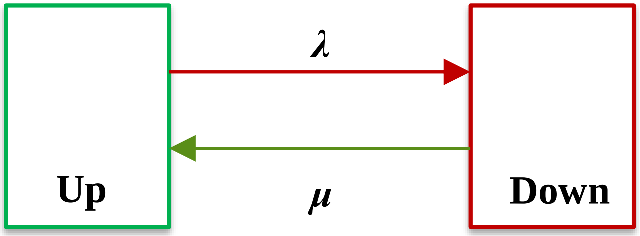


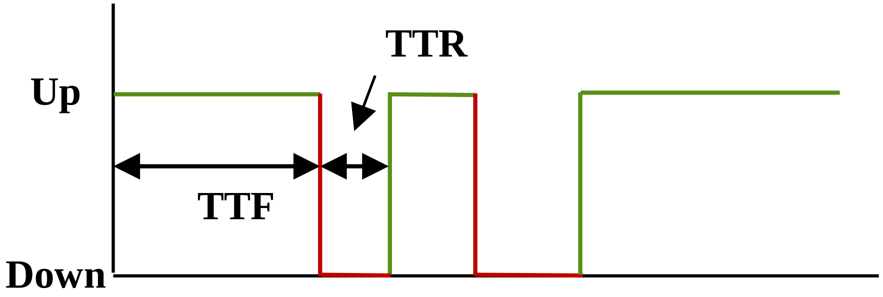


$$F(x;\lambda) = \begin{cases} 1 - e^{-\lambda x}, x \geq 0 \\ 0, x < 0 \end{cases}$$

Reliability models

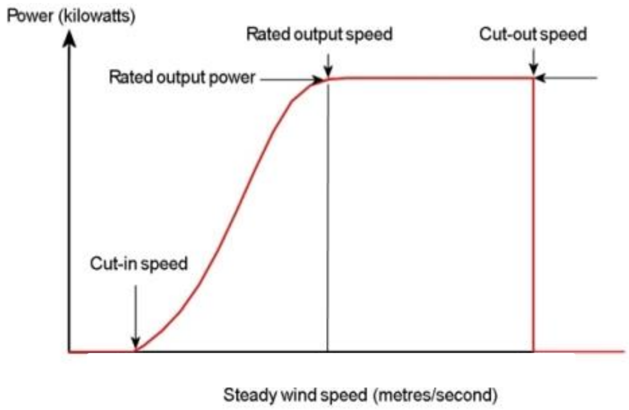
- Conventional generator
  - A two-state Markov model
  - Maximum capacity available in the up-state
- Transmission line
  - Take into consideration line length



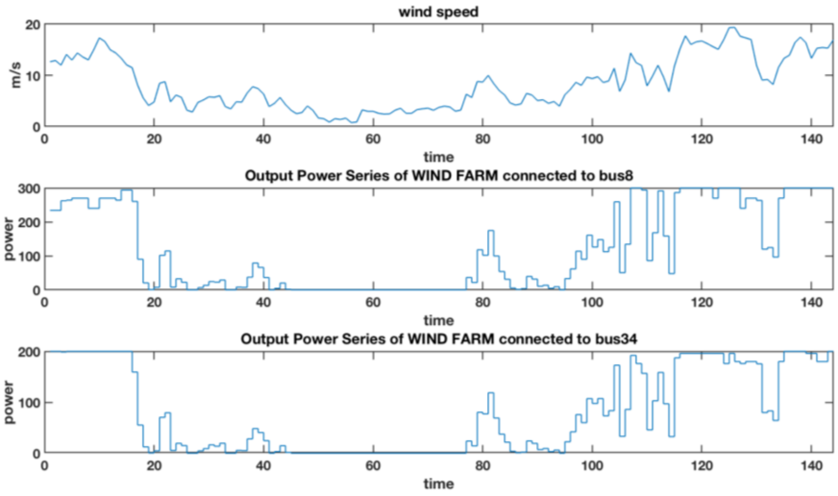


Reliability models

- Wind turbine generator
  - A two-state Markov model
  - Chronological wind speed curve with 1-hour resolution
  - Wind power output based on wind speed and the power curve



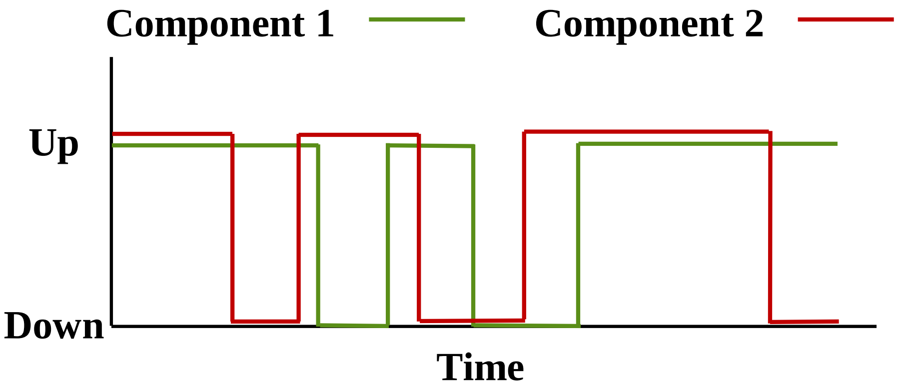
Typical wind turbine power output with steady wind speed.

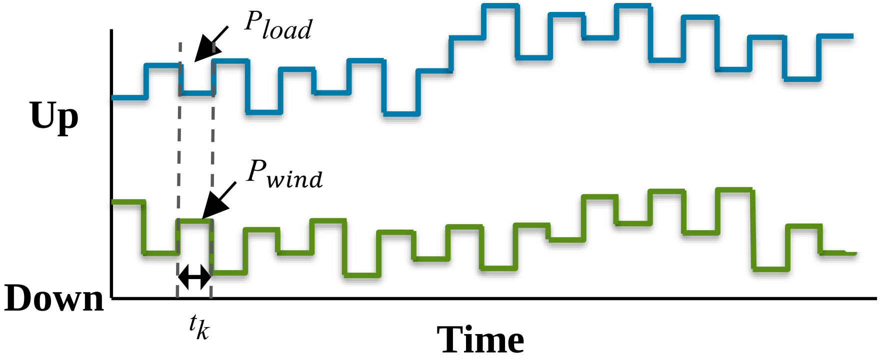


Example of stochastic wind power output using SMCS

Reliability models

- Yearly load curve - the correlation between wind power generation and load is represented
- **Chronological system states** consist of
    - Up/down state of each component
    - Hourly wind power generation
    - Hourly load data
    - Hourly conventional generation





Dynamic models

- **Synchronous generator**
  - Detailed E'' generator model – GENROU
  - Governor model – GGOV1, TGOV1, HYGOV
  - Excitation system model – EXST1

- **Type 3 Wind turbine generator**
  - Generator/ converter model – GEWTG (fault ride through function)
  - Electrical control model – EXWTGE (reactive power control)
  - Turbine and turbine control model – WNDTGE (APC, WindINERTIA)

Dynamic models

- Constant impedance **load model**
- **Protection systems -** to quantify the severity of dynamic insecurity by measuring the amount of load shedding or the amount of generation tripping after a contingency
  - Under-frequency load shedding – LSDT1 in PSLF
  - Under-voltage load shedding – LSDT9 in PSLF
  - Over/ under-frequency generator tripping - GP1 in PSLF
  - Over/ under - voltage generator tripping - GP1 in PSLF

Approach

Adequacy Assessment

- **AC power flow analysis** with remedial actions considered to correct the abnormal system conditions
- PSSE OPF package is used

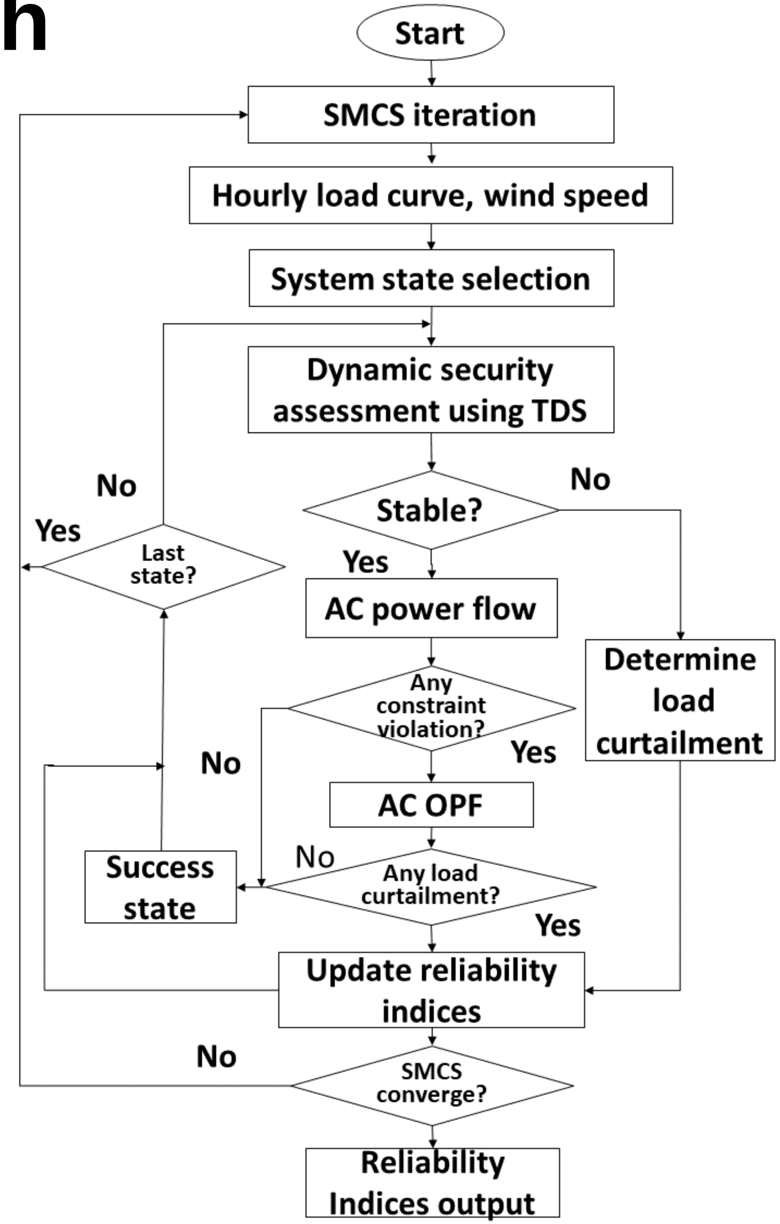
Dynamic Security Assessment

- Time domain simulation tool is used as the assessment method
- Measured by the amount of **load shed** to maintain stability
- The work in S-75 leverages the earlier PSERC project S-55 work on representation of important protection schemes in the transient stability analysis
- Results are brought in reliability indices calculation

Approach

Integrated Evaluation Procedure

- Selecting system states
- Analyzing the system state to judge if it is a failure state
- Calculating reliability indices
- Updating convergence index



Flow chart of integrated evaluation procedure

Acceleration Methods

Two acceleration methods:

- **Cross-entropy based Importance sampling method (CE IS)**
  - **to speed up SMCS**

- **A pruning process for TDS**
  - **to reduce the volume of cases analysed using TDS**

Acceleration Methods

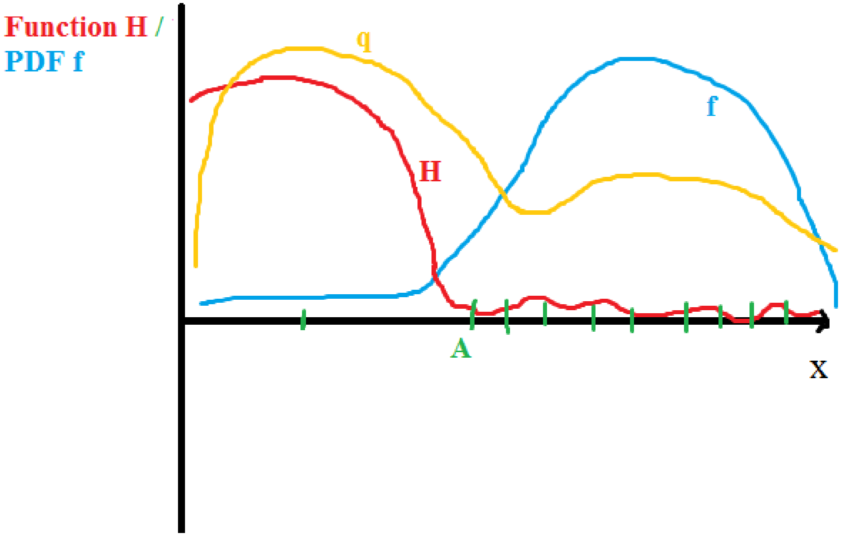
CE IS

- **Importance sampling: certain variables have a greater impact**

Expectation from MCS:

$$E(H(x)) = \int H(x) f(x) dx$$

$$E(H(x)) = \int H(x) \overset{\text{Importance weight}}{\boxed{\frac{f(x)}{q(x)}}} q(x) dx$$

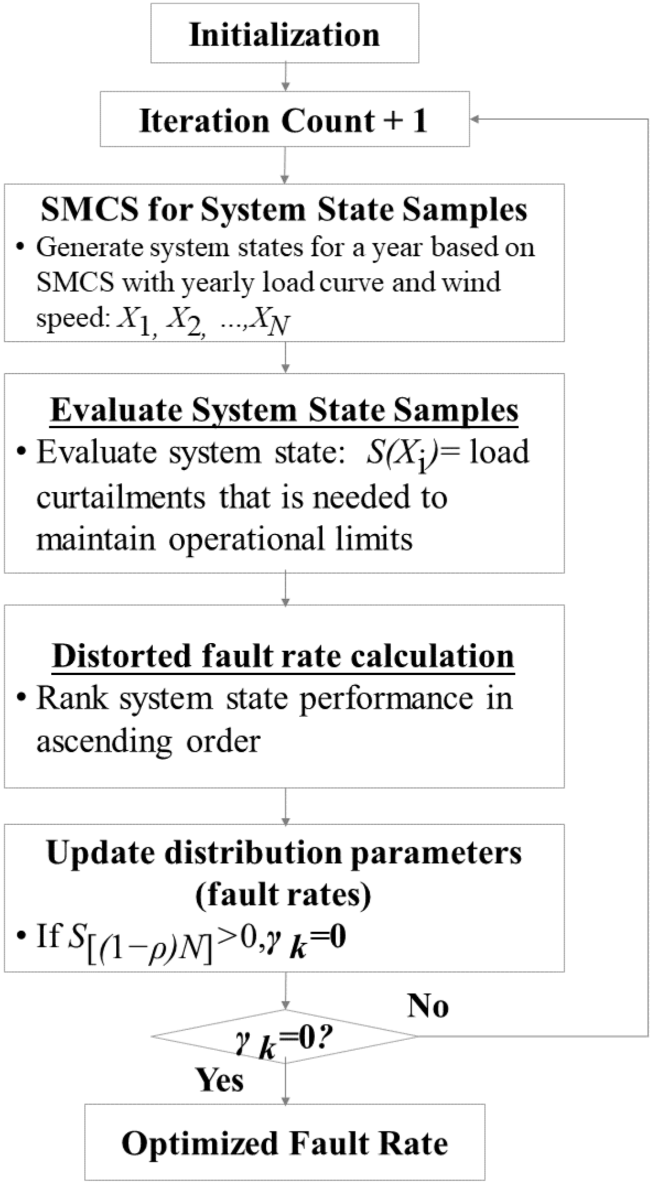


- **The CE method is a Monte Carlo method for importance sampling to obtain the optimal q(x)**

Acceleration Methods

CE IS

- Objective: find optimal fault rate that can facilitate sample more unreliable cases (rare events)
- Criteria of minimizing CE is a certain percentage of sampled cases belongs to rare events



Initialization

Iteration Count + 1

SMCS for System State Samples
- Generate system states for a year based on SMCS with yearly load curve and wind speed: $X_1, X_2, \ldots, X_N$

Evaluate System State Samples
- Evaluate system state: $S(X_i)$= load curtailments that is needed to maintain operational limits

Distorted fault rate calculation
- Rank system state performance in ascending order

Update distribution parameters (fault rates)
- If $S_{[(1-\rho)N]}>0, \gamma_k=0$

$\gamma_k=0?$

No

Yes

Optimized Fault Rate

Acceleration Methods

Pruning process for TDS

- TDS introduces significant computational burden
- A two-stage pruning process is used to reduce simulation burden
  - Conduct an early terminated TDS (5 cycles after the fault occurred)
  - Classify system state to be critical or non-critical based on
    - The corrected kinetic energy (*KE*) gained by the machines due to the fault and
    - The maximum change of Z*th* seen at POI of a generator.

Acceleration Methods

- The corrected kinetic energy (*KE*)
  - Obtain the relative angle and angular speed of generators at the end of the early terminated TDS
  - Calculate the corrected kinetic energy gained by the system, the calculation equation is given as follows:

$$\omega_{coi} = \frac{\sum_{allgens} M_i\, \omega_i}{\sum_{allgens} M_i} \quad (1) \qquad M_{cr} = \sum\nolimits_{critical\ gens} M_{icr} \quad (2) \qquad M_{non\_cr} = \sum\nolimits_{noncritical\ gens} M_{i_{non\_cr}} \quad (3)$$

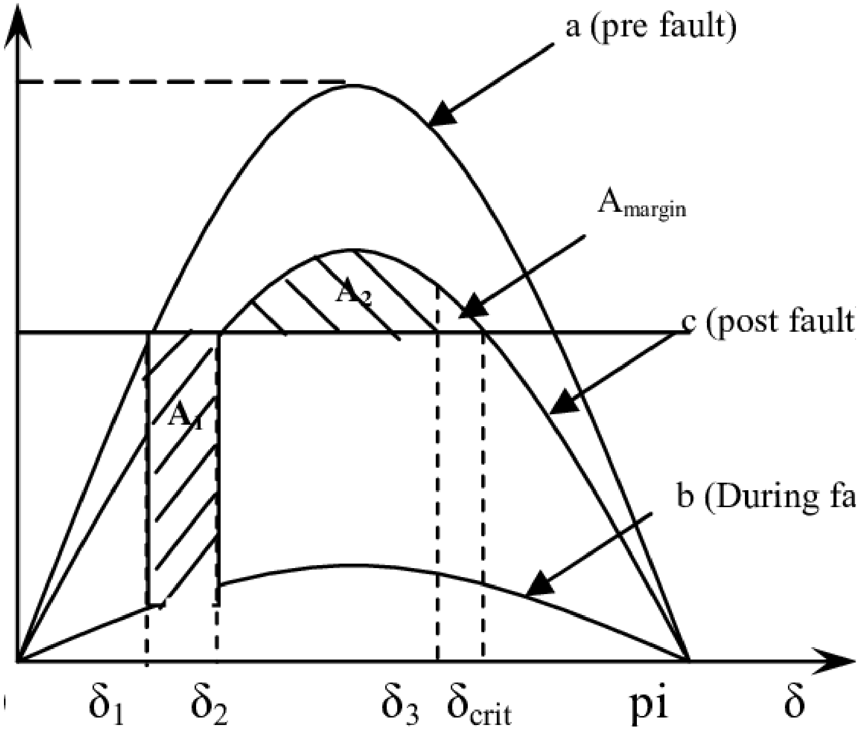
$$\widetilde{\omega}_{cr} = \frac{\sum_{critical\ gens} M_{icr}(\omega_{icr} - \omega_{coi})}{M_{cr}} \quad (4) \qquad \widetilde{\omega}_{non\_cr} = \frac{\sum_{noncritical\ gens} M_{i_{non\_cr}}\left(\omega_{i_{non\_cr}} - \omega_{coi}\right)}{M_{non\_cr}} \quad (5)$$

$$M_{eq} = M_{cr} {*} M_{non\_cr}/(M_{cr} + M_{non\_cr}) \quad (6) \qquad \widetilde{\omega}_{eq} = \widetilde{\omega}_{cr} - \widetilde{\omega}_{non\_cr} \quad (7) \qquad KE_{corr} = \frac{1}{2} M_{eq} (\widetilde{\omega}_{eq})^2 \quad (8)$$

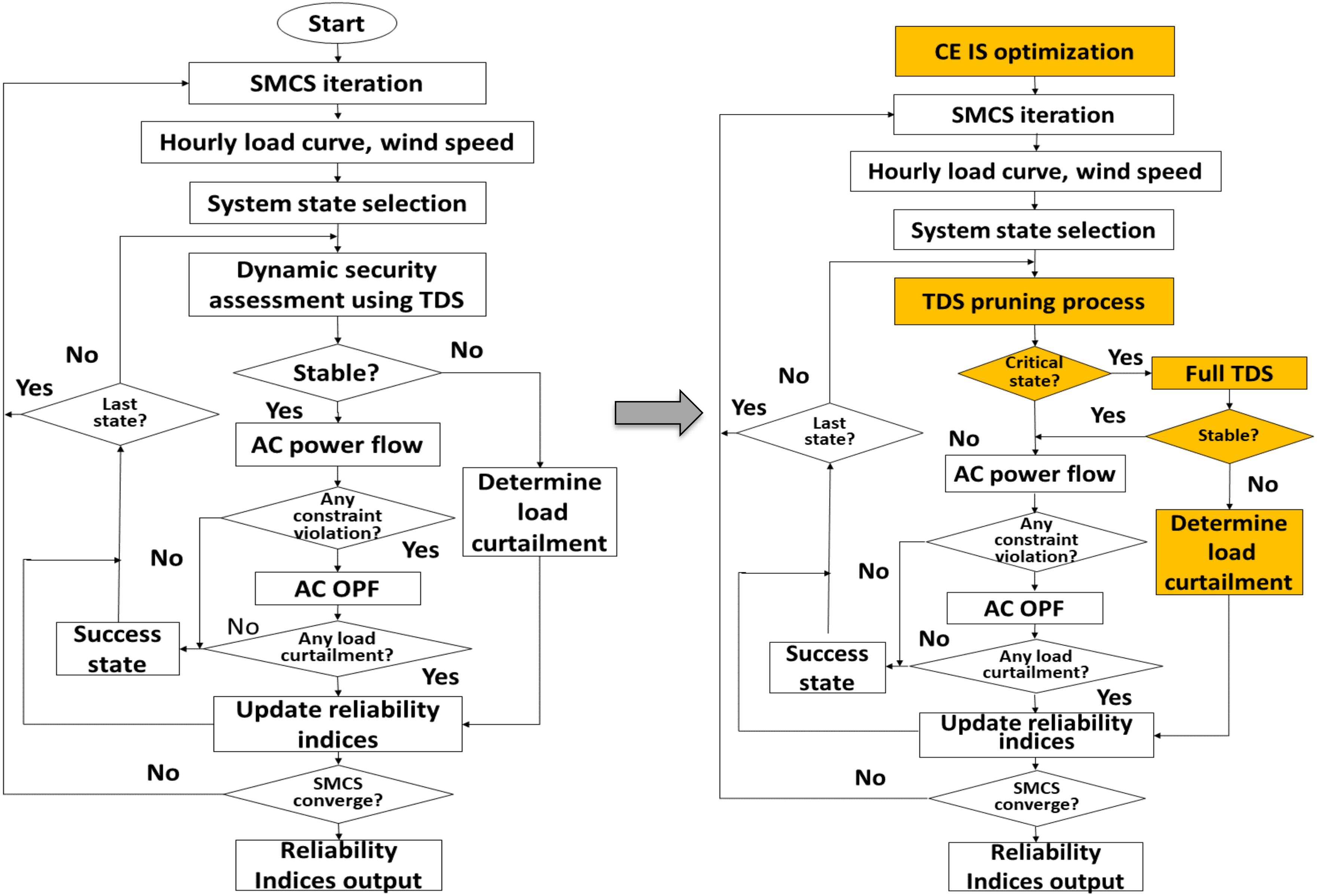
Acceleration Methods

- The max change of Z_{th} - $\Delta\mathrm{Z}_{\mathrm{thmax}}$
  - The max change in the magnitude of Z_{th} is used as an indicator of a critical or non-critical state
  - Since a large change in Z_{th} results in a substantial reduction in the peak of post-fault swing curve

$$2H\frac{d^2\delta}{dt^2} = P_m - \frac{EV}{X}sin\delta$$



Integrated Evaluation Procedure with Acceleration Methods Implemented



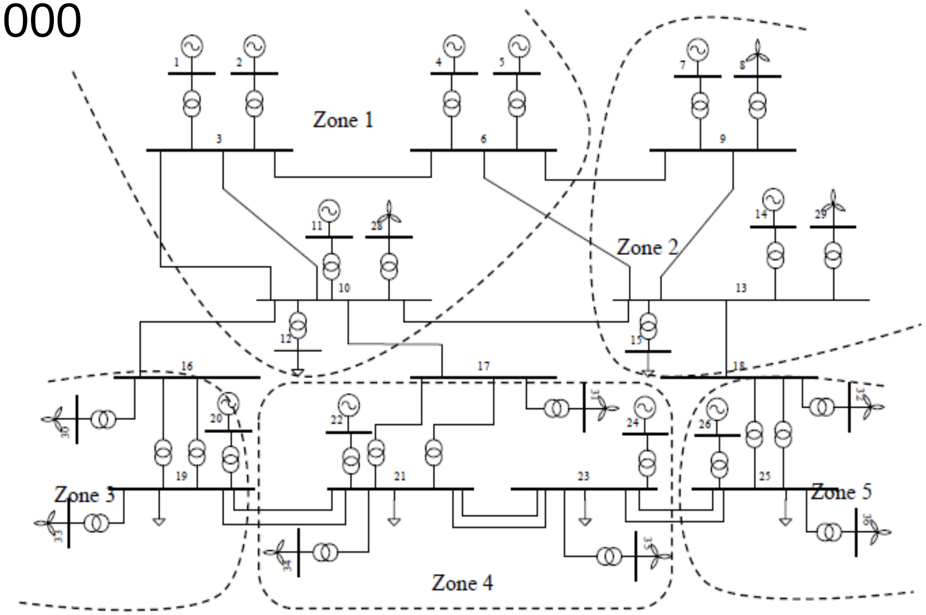
Start
SMCS iteration
Hourly load curve, wind speed
System state selection
Dynamic security assessment using TDS
Stable?
No
Yes
AC power flow
Determine load curtailment
Any constraint violation?
Yes
No
AC OPF
Any load curtailment?
No
Yes
Success state
Last state?
No
Yes
Update reliability indices
SMCS converge?
No
Reliability Indices output

CE IS optimization
SMCS iteration
Hourly load curve, wind speed
System state selection
TDS pruning process
Critical state?
Yes
Full TDS
Stable?
Yes
No
Determine load curtailment
No
AC power flow
Any constraint violation?
No
AC OPF
Any load curtailment?
No
Yes
Success state
Last state?
No
Yes
Update reliability indices
SMCS converge?
No
Reliability Indices output

Study cases

Test System

- **A synthetic power system**
  - 11 synchronous generators with 17,000 MW total capacity
  - 10 wind plants with 1,680 MW total capacity
  - 20 transmission lines
  - Simulation in GE PSLF
- **Reliability data**
  - Transmissions fault data: ‘forced outage performance of transmission equipment report’-CEA
  - Generator fault data and load curve from IEEE RTS system



Simulation 1
System adequacy evaluation results

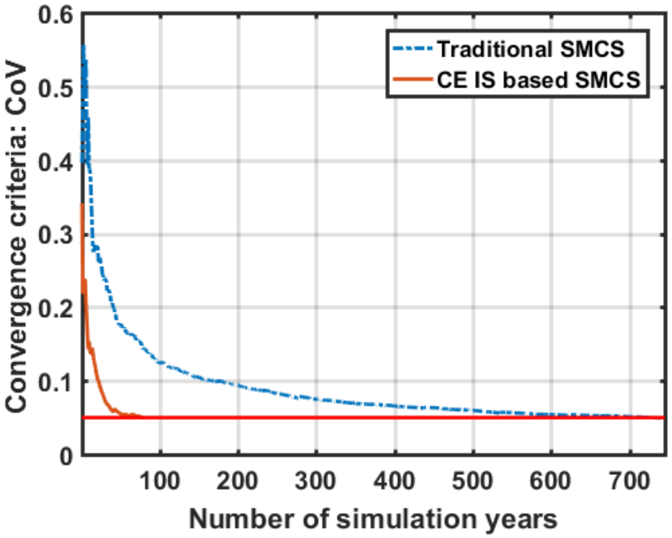
- **Traditional SMCS addressing only composite system adequacy**
  - The system peak load is 7612 MW + j2108 MVAr.
- **The simulation converges after 746 iterations. Reliability indices results are:**
  - LOLP: 0.0015
  - EPNS: 0.0087 MW
  - LOLF: 2.7663 occ./ year.

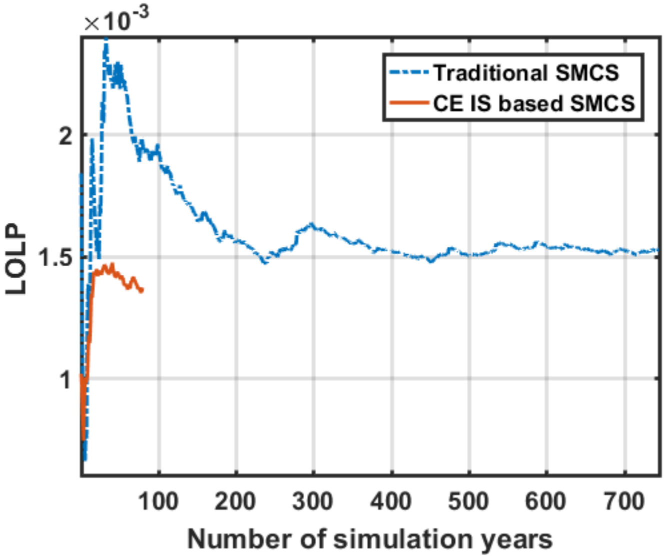
Iterations	**COV criteria**	**LOLP**	**EPNS (MW)**	**LOLF (occ./y)**
746	5%	0.0015	0.0087	2.7663

Simulation 2
Impact of accelerating techniques

- **Reliability indices comparison: traditional SMCS and CE-IS SMCS (9.21 times speed-up!)**

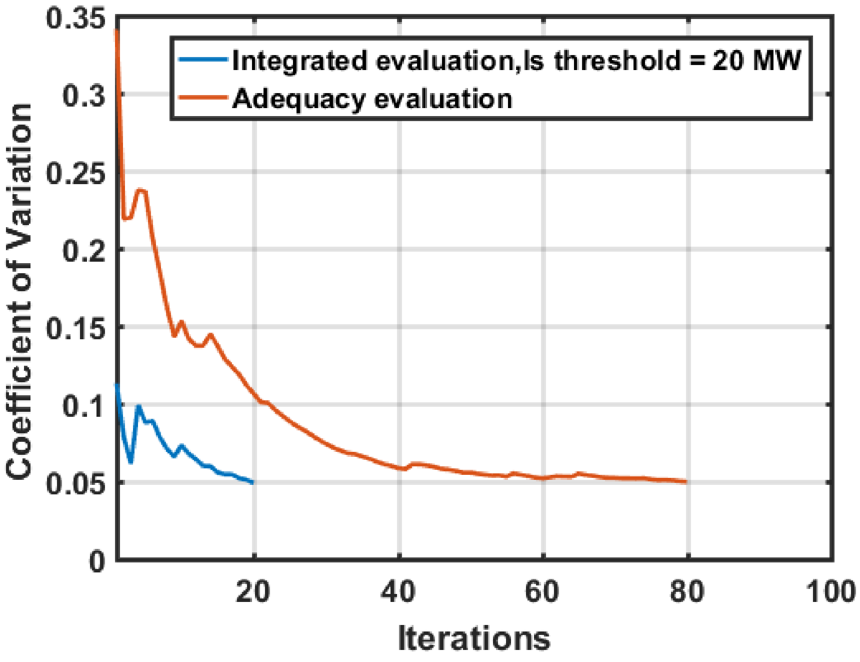
Method	**Iterations**	**COV criteria**	**LOLP**	**EPNS (MW)**	**LOLF (occ./y)**	**Computation time**
Traditional SMCS	746	5%	0.0015	0.0087	2.7663	8.95×10^5s (248 h)
CE-IS SMCS	81	5%	0.0014	0.0079	2.7650	0.98×10^5s (27 h)

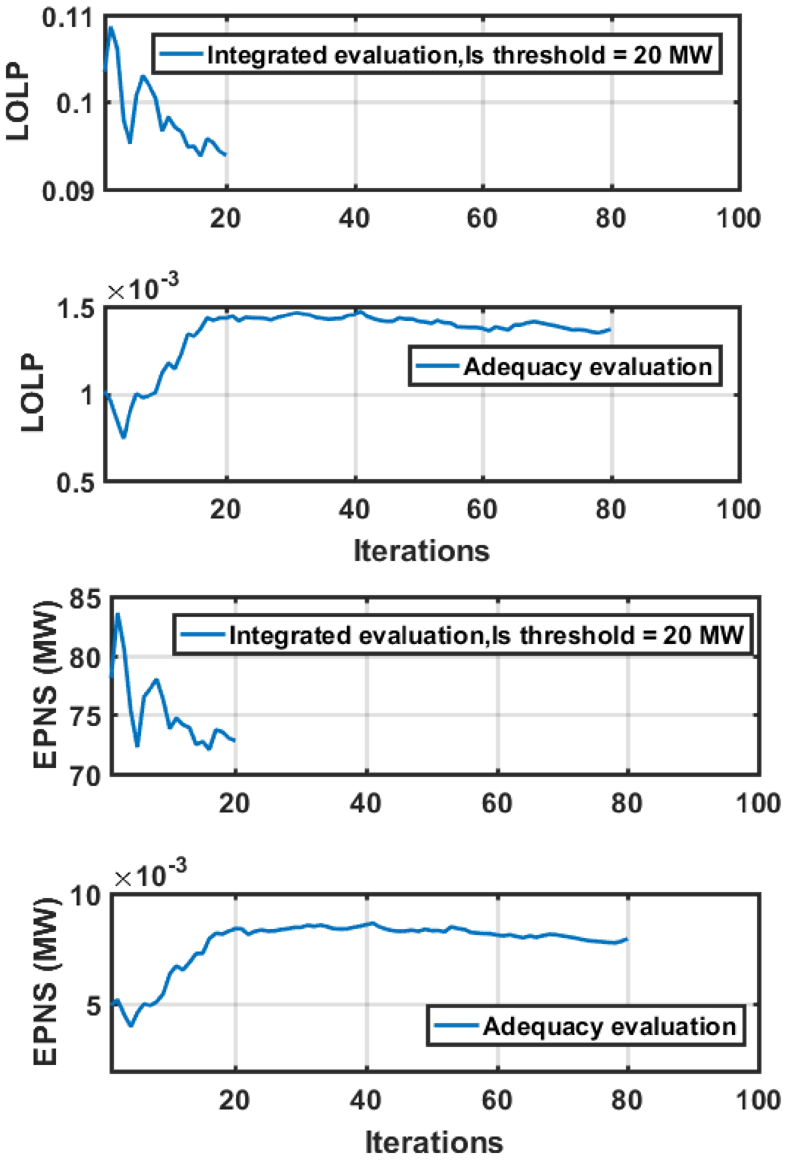




Simulation 3:
Integrated reliability evaluation results

- **Both with CE-IS**
- **Convergence: 20 vs. 81 iterations**
- **LOLP: 0.0939 vs. 0.0014**
- **EPNS: 72.8 MW vs. 0.0079 MW**





Simulation 3:
Integrated reliability evaluation results

❑ Statistical summary

Among 11992 system states

- 408 cases are steady-state unreliable
- 4603 cases are steady-state reliable yet dynamically insecure
  - 8 cases are N-1 contingencies
  - 4595 cases are N-k contingencies with k>1.

➢ **Reliability study will give optimistic results if the DSA is not considered.**

Simulation 3: Integrated reliability evaluation results

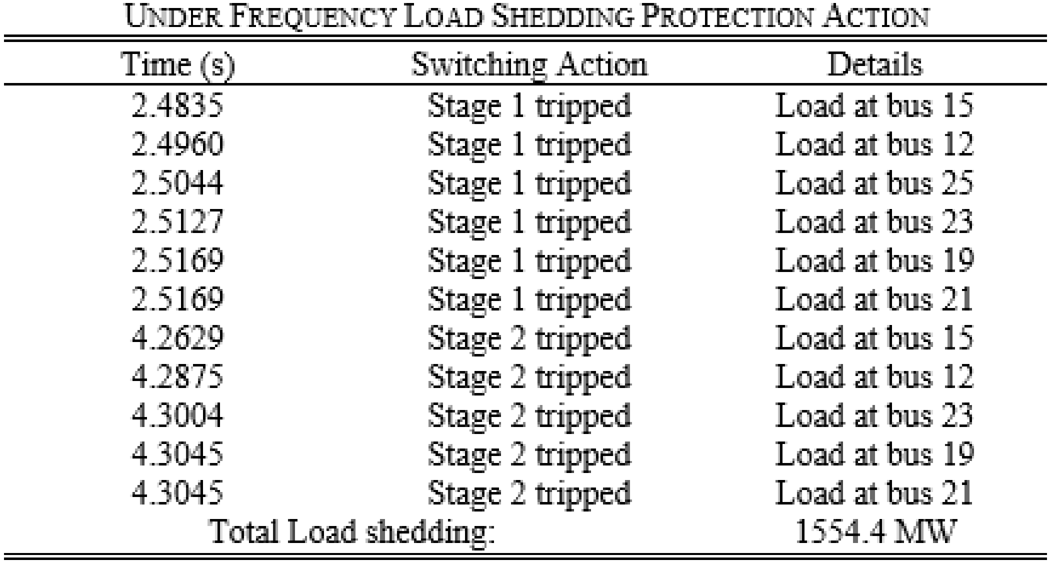
- Pre-contingency condition
  - All generators and transmissions are online
  - 6375 MW load and 6581 MW generation

No.	Outage component	Rating (MVA)	Pre-fault condition	Fault at time
1	Gen6 on bus 24	4500	1849.3 MW generation	1 s
2	Gen8 on bus 26	1200	405.9 MW generation	1 s
3	Wind farm on bus 808	33.4	9.80 MW generation	1 s
4	Wind farm on bus 3404	23.4	6.90 MW generation	1 s
5	Wind farm on bus 3405	23.4	6.90 MW generation	1 s
6	Line from bus 13 to bus 18	1500	488.6 MW flow	1 s

Contingency setting

Simulation 3: integrated reliability evaluation effect

- **For this case:**
  - **Adequacy assessment result: 0.185 MW load curtailment**
  - **DSA result: 1554.4 MW load shed**



UNDER FREQUENCY LOAD SHEDDING PROTECTION ACTION

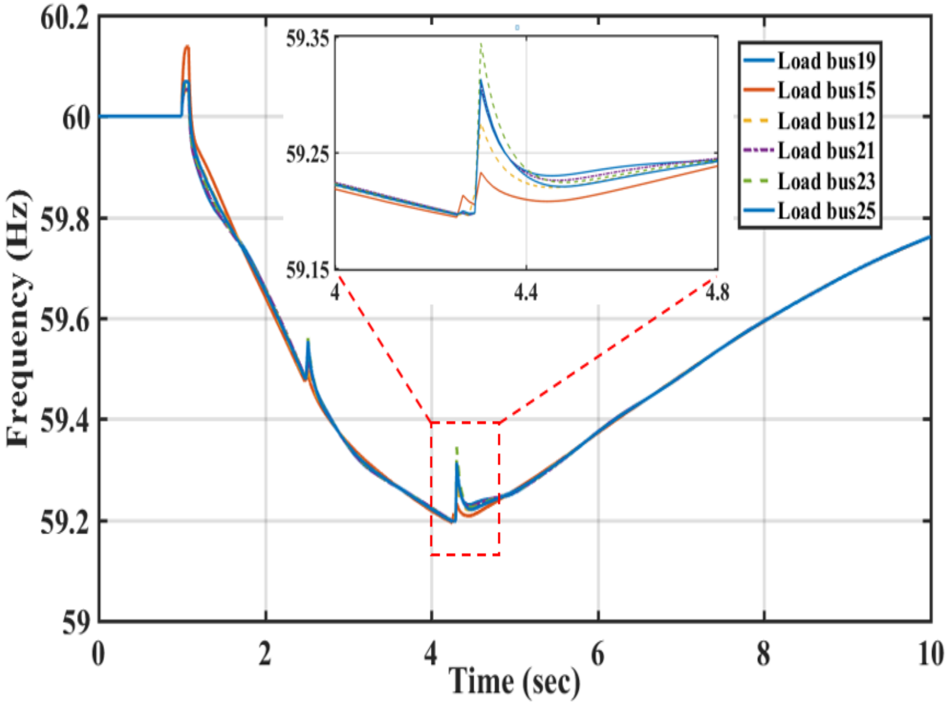
Time (s)	Switching Action	Details
2.4835	Stage 1 tripped	Load at bus 15
2.4960	Stage 1 tripped	Load at bus 12
2.5044	Stage 1 tripped	Load at bus 25
2.5127	Stage 1 tripped	Load at bus 23
2.5169	Stage 1 tripped	Load at bus 19
2.5169	Stage 1 tripped	Load at bus 21
4.2629	Stage 2 tripped	Load at bus 15
4.2875	Stage 2 tripped	Load at bus 12
4.3004	Stage 2 tripped	Load at bus 23
4.3045	Stage 2 tripped	Load at bus 19
4.3045	Stage 2 tripped	Load at bus 21
Total Load shedding:		1554.4 MW

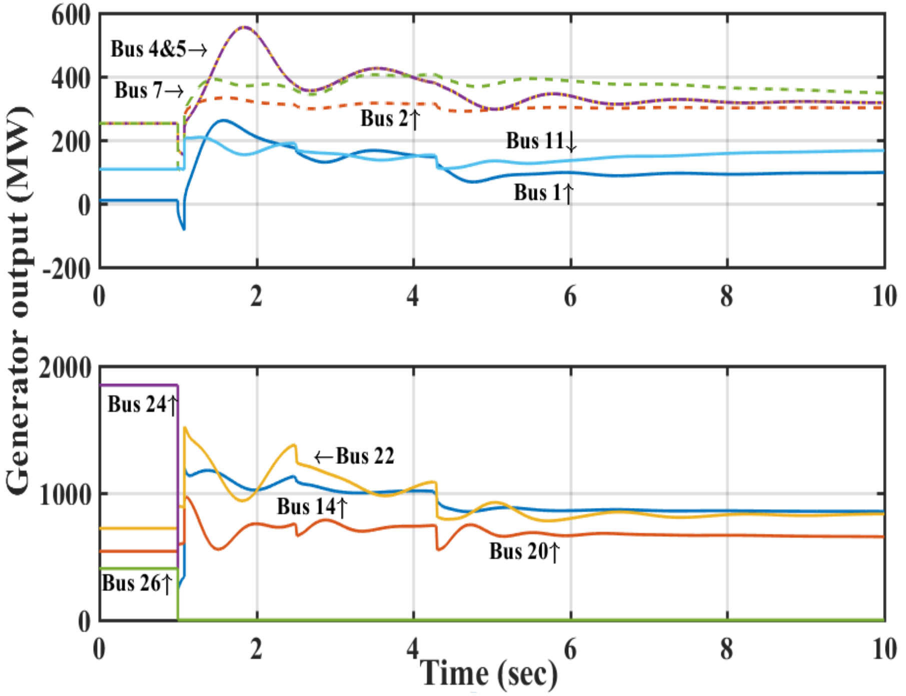
Simulation 3:
Integrated reliability evaluation results

- ❑ Case study:

- ➢Adequacy assessment result: 0.185 MW load curtailment

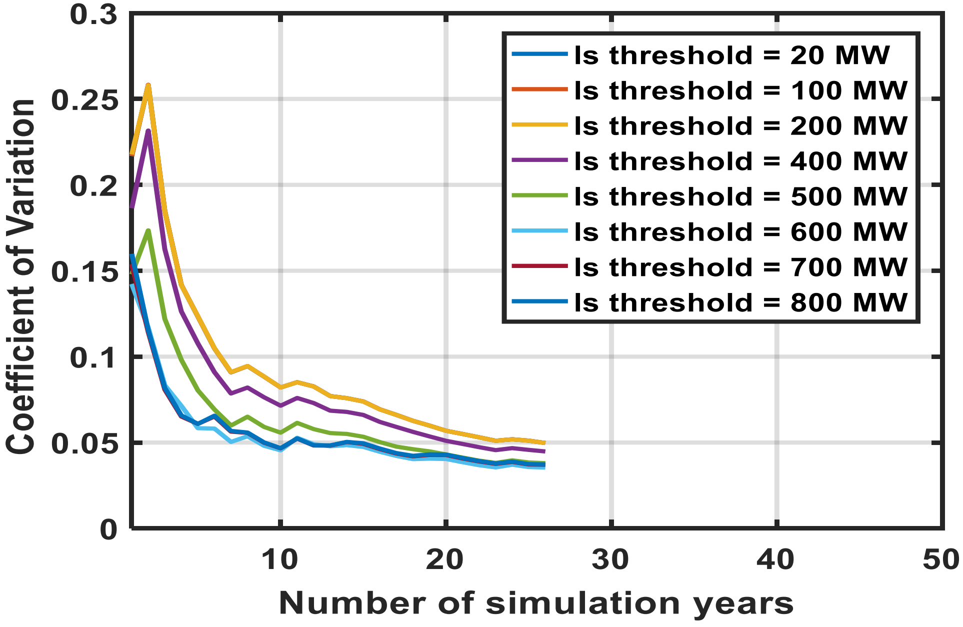
- ➢DSA result: 1554.4 MW load shed

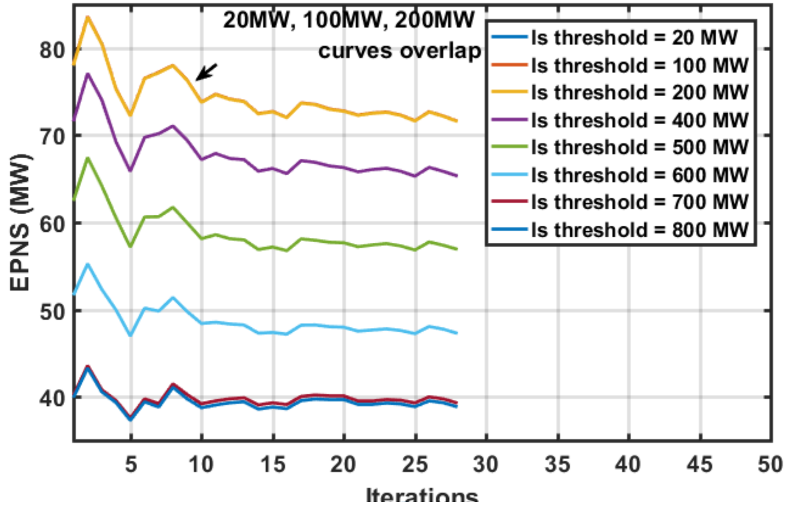


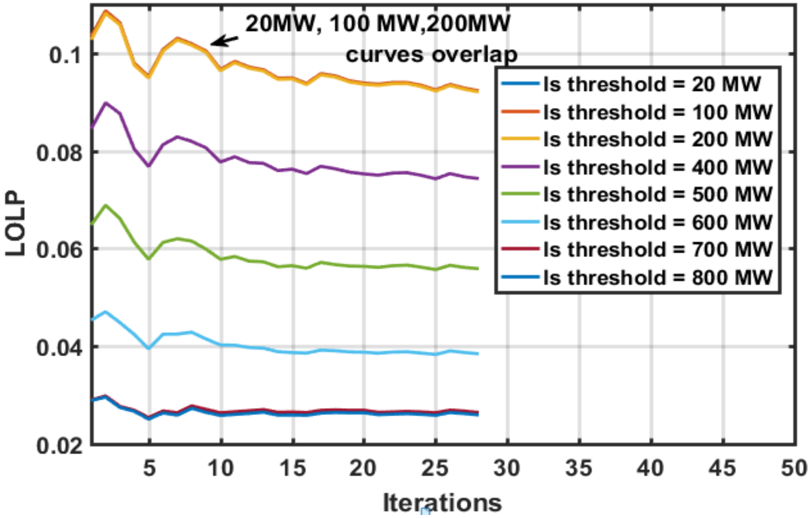


Simulation 4:
Sensitivity study for the load shed threshold in TDS

- ❑ **Sensitivity study for load shed threshold in TDS**
- ❑ Very similar results from simulations with LS threshold as 20 MW, 100 MW, and 200 MW







Simulation 5:
TDS pruning process effects

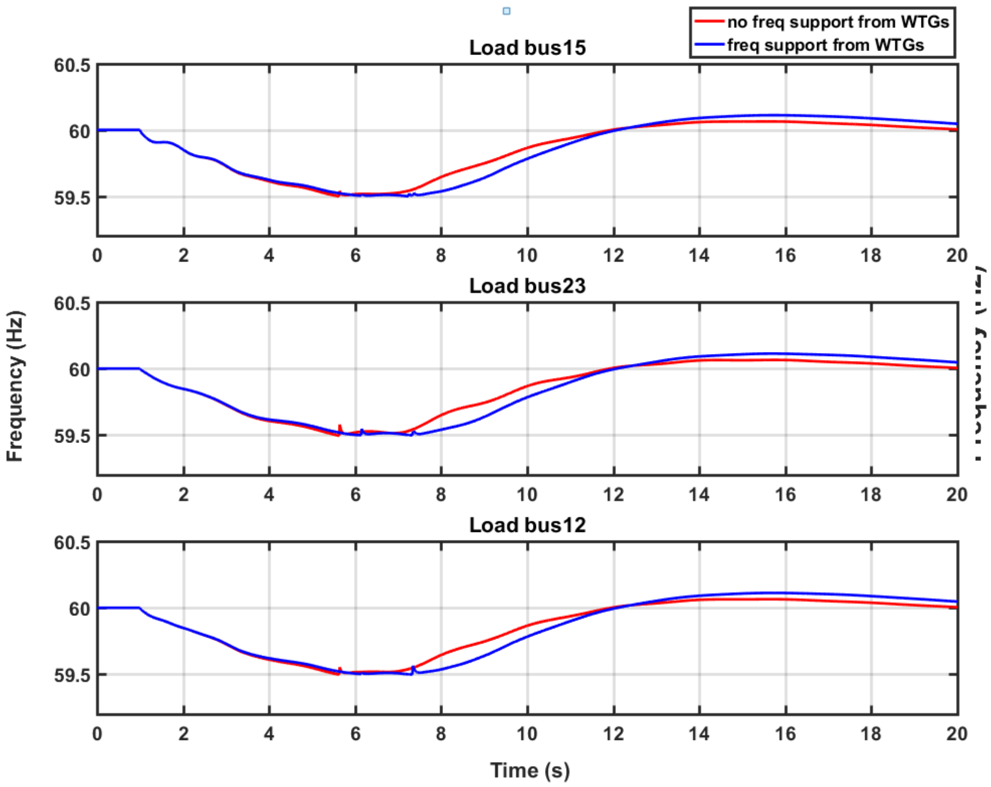
- With pruning: 3842 states out of 11992 states have been pruned out of full TDS (32% cases)

LS_{TDS} criteria (MW)	Without Pruning Process	With Pruning Process	Deviation (%)
20	0.0939	0.0916	2.4494
100	0.0939	0.0916	2.4494
200	0.0936	0.0913	2.4573
400	0.0753	0.0721	4.2497
500	0.0564	0.0536	4.9645
600	0.0388	0.0375	3.3505
700	0.0269	0.0259	3.3457
800	0.0264	0.0257	2.2727
Average deviation:			**3.1924**

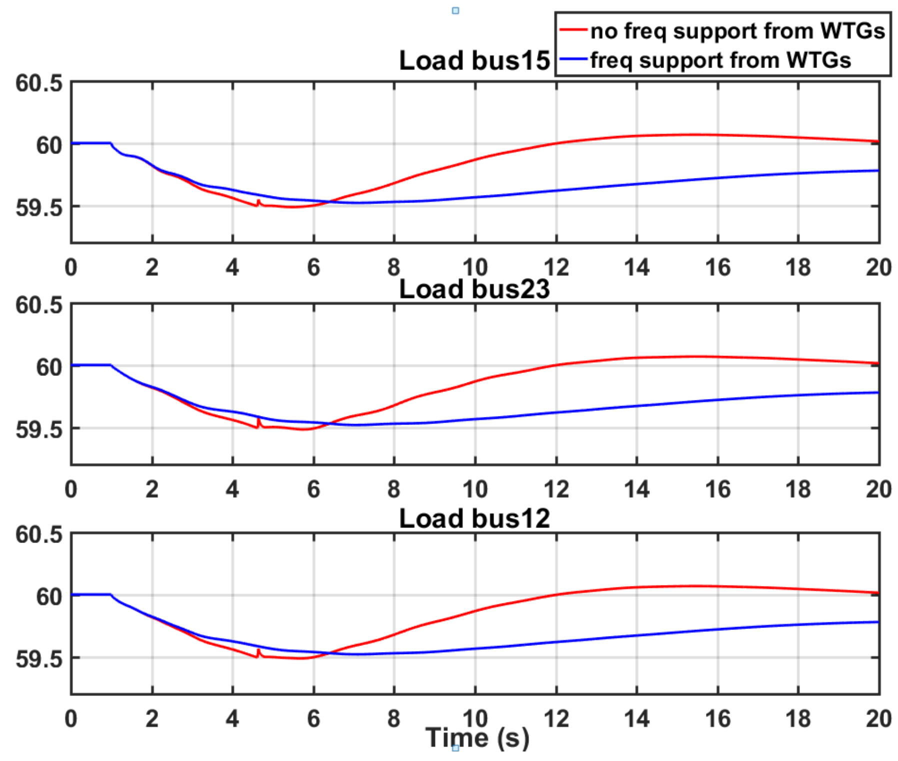
Simulation 6:
Frequency support assessment

- Installation capacity: 17050 MW + 1680 MW = 18730 MW, 14463 MW load
- outage: 1345.8 MW generation trip

11% wind penetration
(1447 MW load shedding)



22% wind penetration
(1447 MW vs. no load shedding)



Conclusions

- Results showed the importance of considering dynamic security in reliability evaluation
- Stochastic and time variant characteristics can easily be considered in the evaluation using SMCS
- The proposed approach can quantify the integrated reliability
- The two acceleration methods are effective in speeding up the evaluation process
- A paper has been submitted and revised for resubmission, based on the results.
- Another paper focusing on using the integrated reliability evaluation approach to include the assessment of frequency and voltage support is being prepared.

Future work

- Include voltage support capability evaluation into the work
- The second paper
- Final project report

Questions?

Chanan Singh, TAMU
Vijay Vittal, ASU
Mojdeh Khorsand, ASU

Chanan Singh: singh@ece.tamu.edu
Vijay Vittal: vijay.vittal@asu.edu
Mojdeh Khorsand: mojdeh.khorsand@asu.edu