Cyber-physical Interactions and Power Grid Reliability

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Introduction

- Modern power systems: integration of current carrying components (for power delivery), monitoring, computing, communication and protection systems.
- Human interface - power systems are not fully automated
- Complexity is increasing with more monitoring, control and communications
- Sources of failure:
  - physical components (power/current carrying),
  - failures in cyber network – hard and soft,
  - human failures
- Contemporary power system reliability methods focused almost entirely on the failure of physical components

Solution approaches in power system reliability evaluation

- **Analytical methods: mostly used in single, multi-area and distribution system models.**
- **Monte Carlo simulation; mostly used in multi-area and composite system models.**
- **Intelligent search techniques: still in development stage for either increasing the efficiency of analytical or simulation or providing an alternative to Monte Carlo simulation.**
- **Hybrid: mixing for increased strength.**
- **An assumption running through the developed models and methods is that of independence of components and that cyber part is perfectly reliable.**

Emerging Power Systems

- **Power systems of the future are emerging to be different.**
- **Two major factors contributing to this change:**
  - **Large penetration of renewable energy sources**
  - **Increasing complexity of cyber part.**
- **Installation of hardware for interactive relationship between the supplier and consumer will add to complexity and interdependency between the cyber and physical parts.**
- **Complexity and interdependency will introduce more sources of problems and make reliability analysis more challenging but also more essential.**

Introduction

Cyber-Physical Security and Reliability

Cyber Security: Studies deliberate cyber attack scenarios, consequences, and prevention or mitigation strategies.

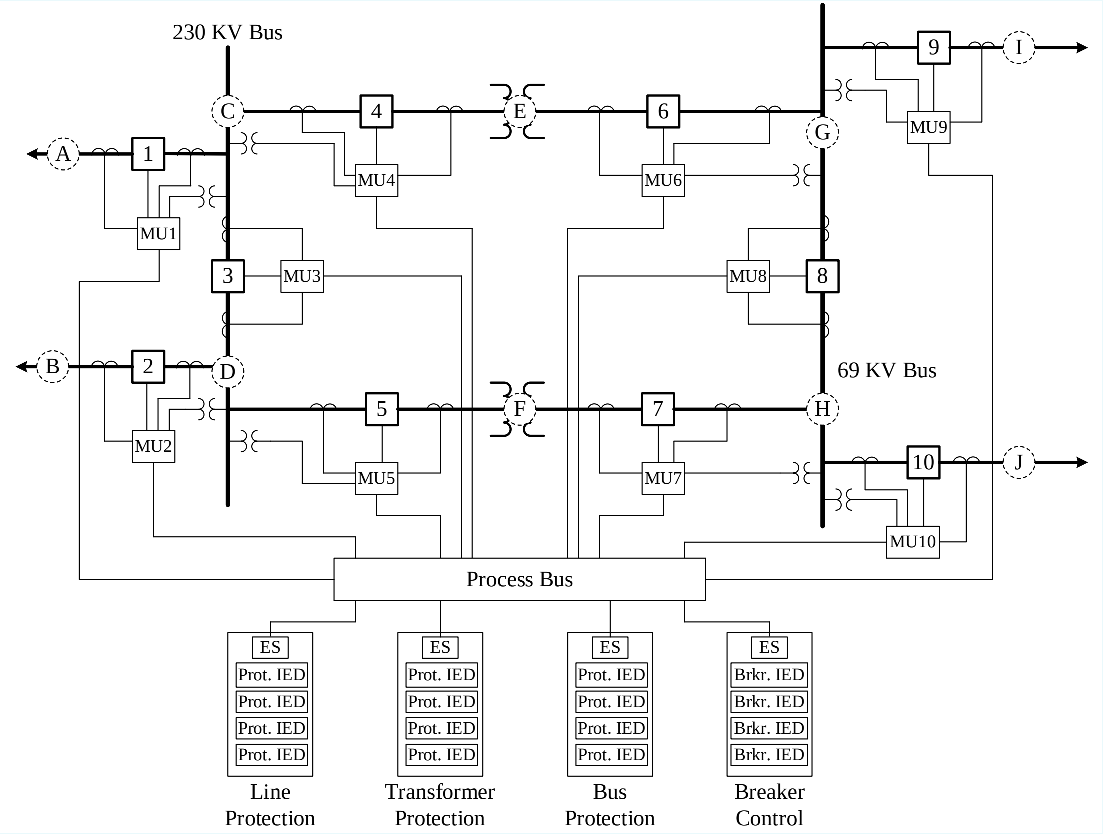
Cyber Reliability: Studies intrinsic failure modes of cyber related components and their impact on power system reliability.

Ultimately both impact the reliability of power supply but the two may require different modeling and methodology.

Cyber- Physical Interaction

- The concepts and approaches will be explained using an example of a substation.
- The problems, however, extend across the entire grid.

Digital Substation as a Cyber-Physical System



An IEC 61850 based protection system for a 230-69 kV substation

Physical Components (Power-Carrying Components):

Transmission Lines

Power Transformers

Circuit Breakers

Cyber Components:

CTs/PTs

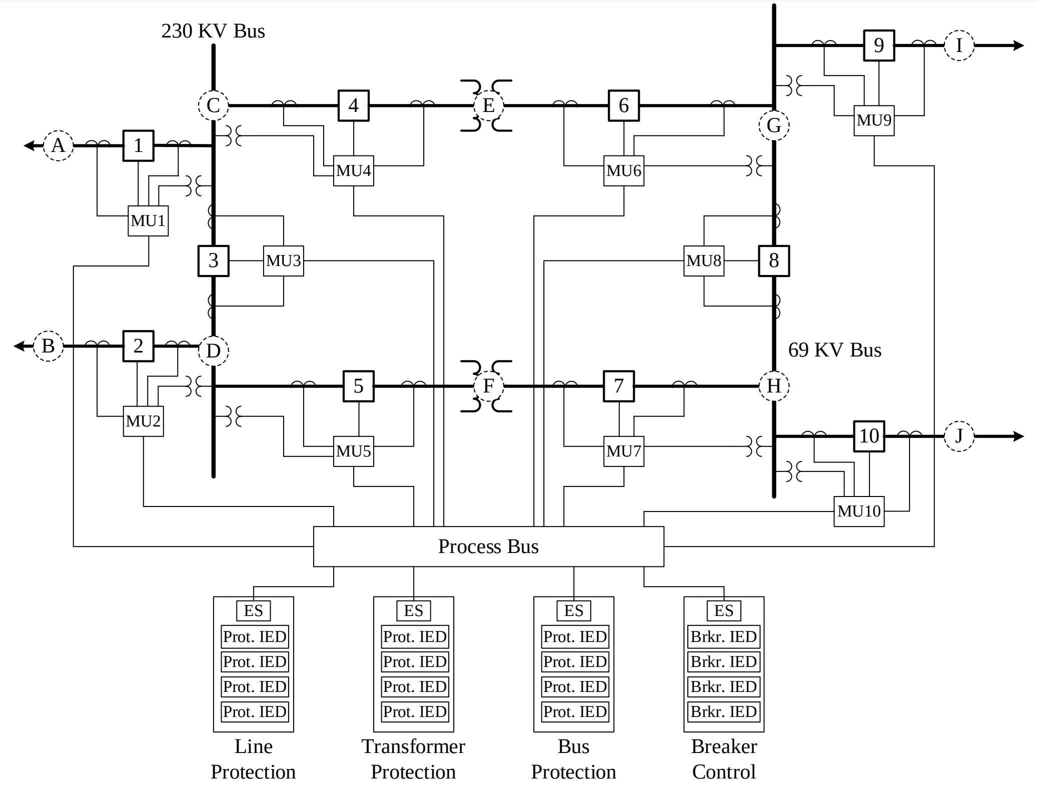
Merging Units

Process Bus

Ethernet Switches

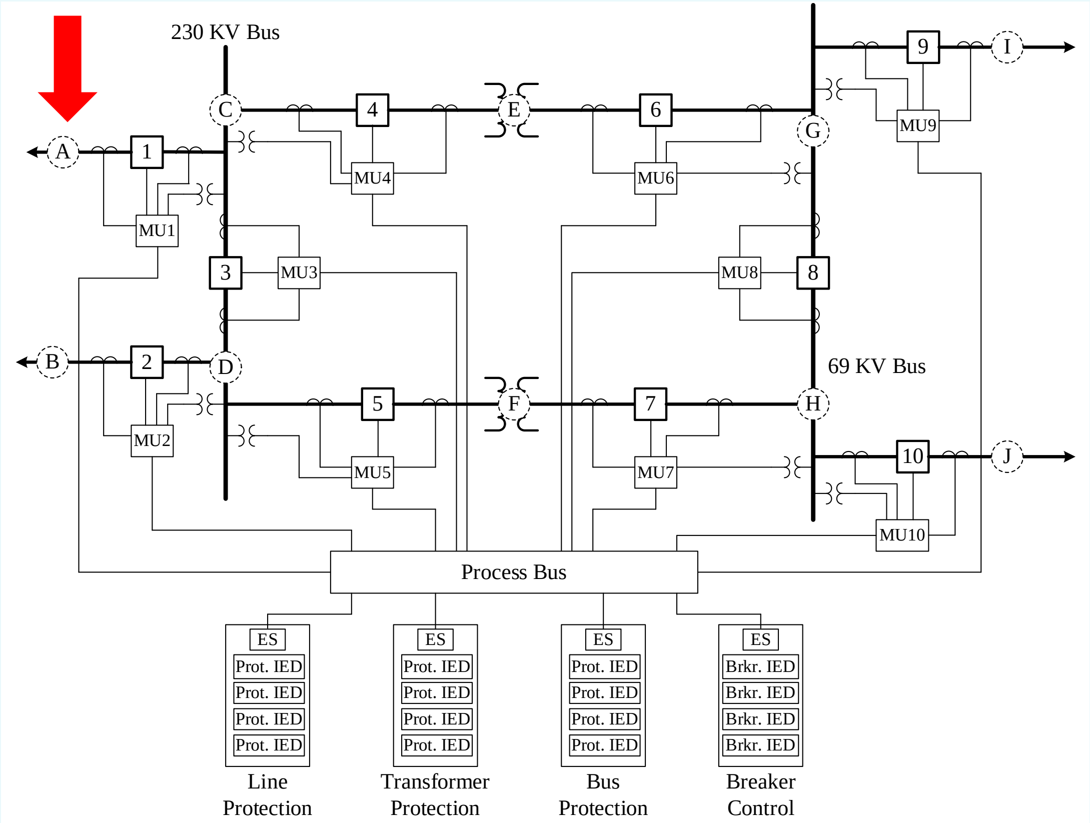
Protection IEDs

Protection Zone Division



Type	Fault Locations	Associated Circuit Breakers
Line	A	Breaker 1
	B	Breaker 2
	I	Breaker 9
	J	Breaker 10
Transformer	E	Breakers 4, 6
	F	Breakers 5, 7
Bus	C	Breakers 1, 3, 4
	D	Breakers 2, 3, 5
	G	Breakers 6, 8, 9
	H	Breakers 7, 8, 10

How of Cyber-Physical Interdependency



Analysis:
Primary fault on Line A

**Other* :
One or more components of MU1, Line Protection Panel, CB1 fail to operate. Or Process Bus is in delay state

Failure Modes	Physical Components Affected	Probability
Protection all good	Only Line A	0.996957511
Process bus failed	Entire Substation	0.000009132
*Other**	Line A and Bus C	0.003033357

Cyber-Physical Interdependency

Analysis: Primary fault on Line B

Physical Components Affected	Probability
Only Line B	0.996957511
Entire Substation	0.000009132
Line B and Bus D	0.003033357

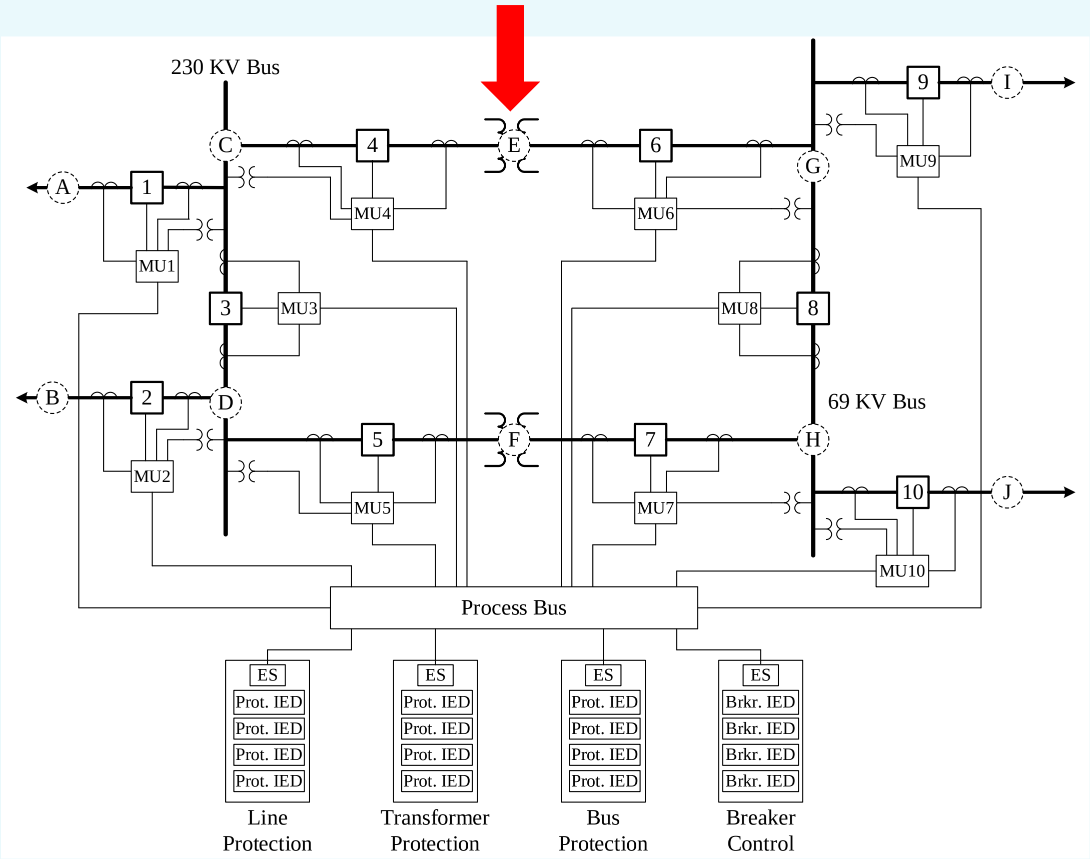
Analysis: Primary fault on Line I

Physical Components Affected	Probability
Only Line I	0.996957511
Entire Substation	0.000009132
Line I and Bus G	0.003033357

Analysis: Primary fault on Line J

Physical Components Affected	Probability
Only Line J	0.996957511
Entire Substation	0.000009132
Line J and Bus H	0.003033357

Cyber-Physical Interdependency

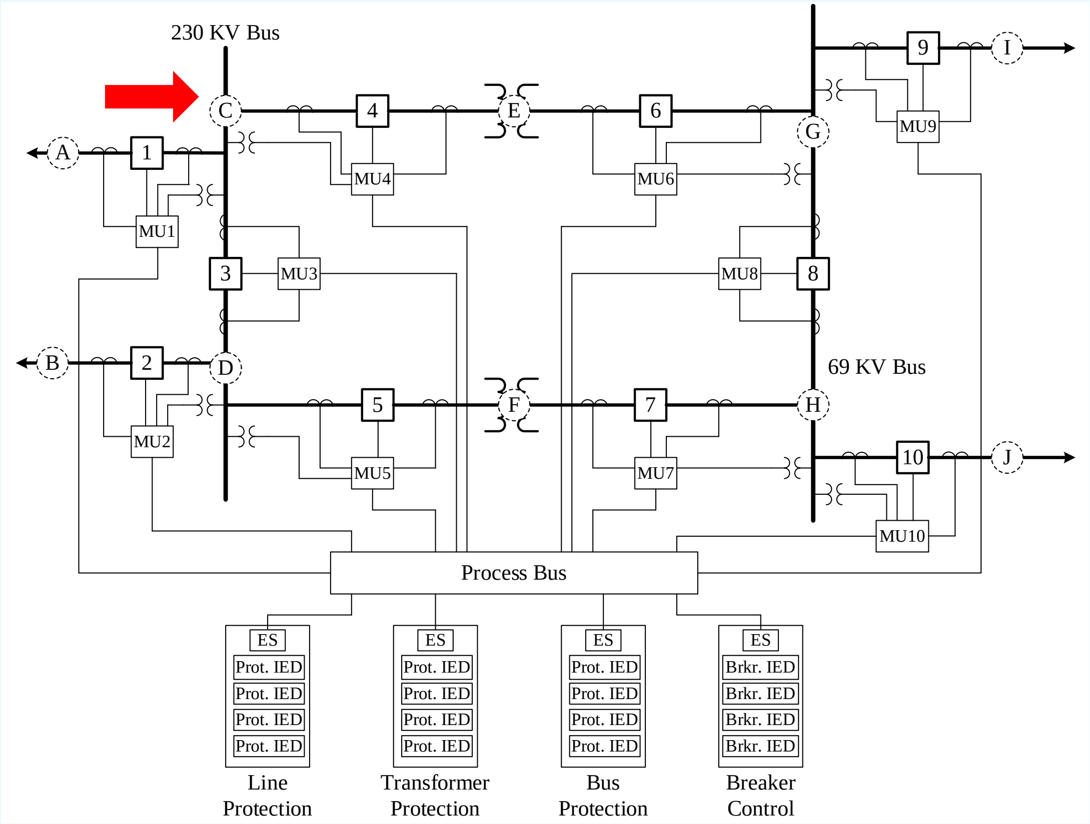


Analysis:

Primary fault on Transformer E

Physical Components Affected	Probability
Only E	0.996942336
Entire Substation	0.000009132
E and C	0.000015174
E and G	0.000015174
E, C, and G	0.003018182

Cyber-Physical Interdependency



Analysis:

Primary fault on Bus C

Physical Components Affected	Probability
Only C	0.996927163
Entire Substation	0.000009132
A and C	0.000015174
C and D	0.000015174
C and E	0.000015174
A, C, and D	$2.31*10^{-10}$
A, C, and E	$2.31*10^{-10}$
C, D, and E	$2.31*10^{-10}$
A, C, D, and E	0.003018182

Representing interdependency for Reliability Analysis

Cyber-Physical Interface Matrix (CPIM)

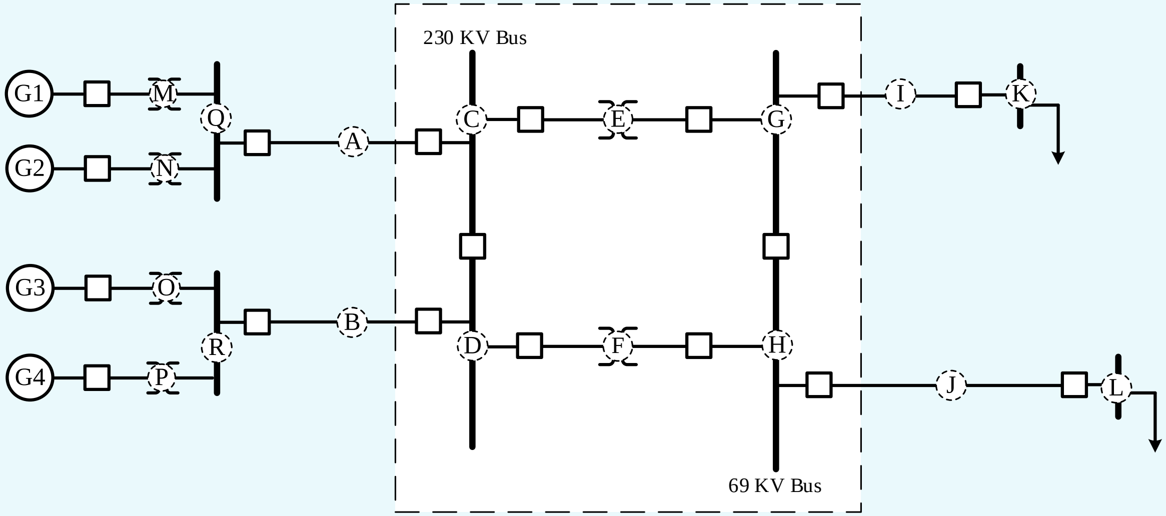
Line A	0.9969575	0.0000091	0.0030334	0	……
Line B	0.9969575	0.0000091	0.0030334	0	……
Line I	0.9969575	0.0000091	0.0030334	0	……
……	……	……	……	……	……
Bus H	0.9969272	0.0000091	0.0000152	0.0000152	……

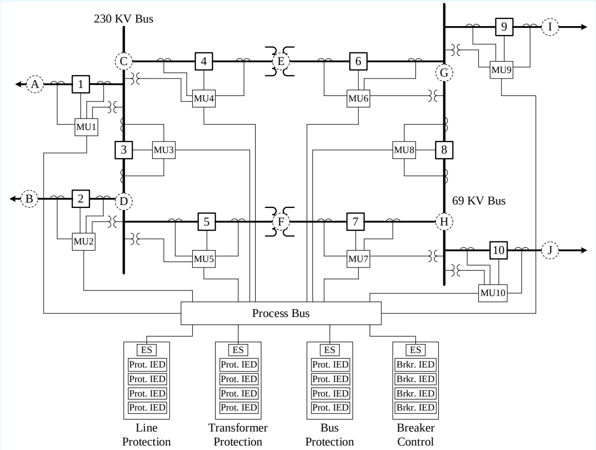
Consequent Events Matrix (CEM)

Line A	Event-1	Event-2	Event-3	Event-4	
Line B					
Line I					
……	……	……	……	……	……
Bus H					

System-wide Reliability Evaluation

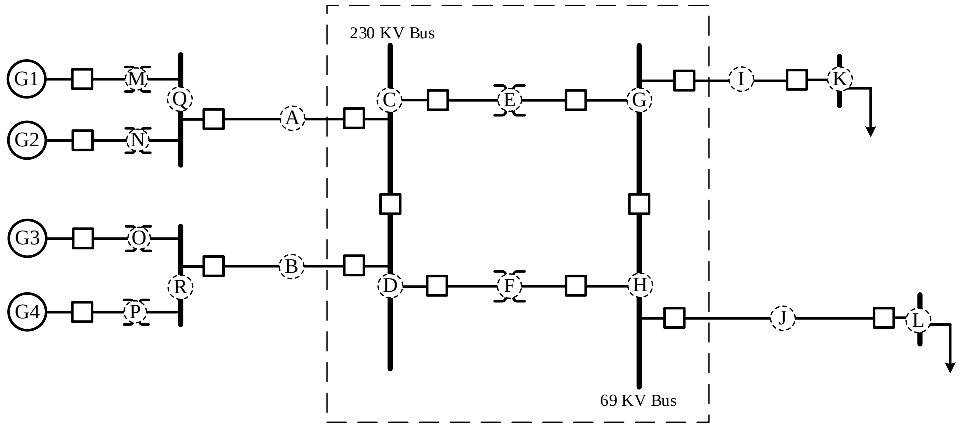
Composite system reliability evaluation with the use of cyber-physical interface matrix





Monte Carlo Simulation

Composite system reliability evaluation with the use of cyber-physical interface matrix



Step 1: Set the initial state of all components as UP and set the simulation time $t = 0$.

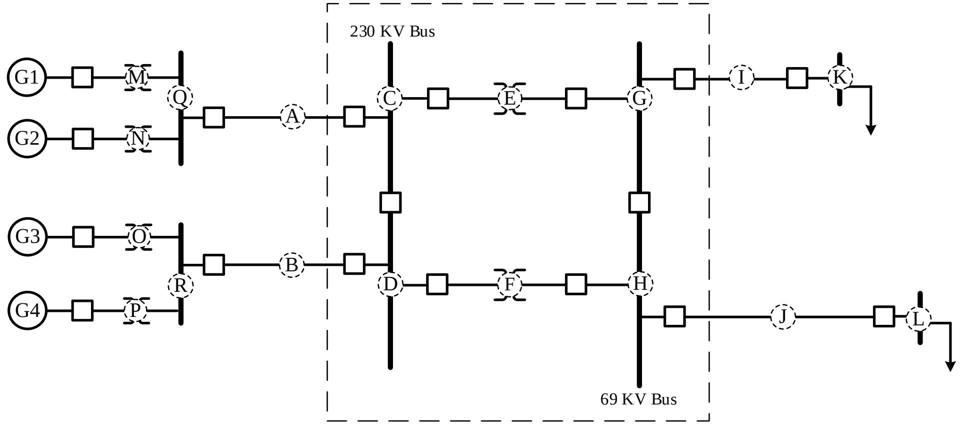
Step 2: For each individual component, draw a random decimal number z_i between 0 and 1 to compute the time to the next event.

$$T_i = -\frac{ln(z_i)}{\rho_i}$$

Depending on whether the i^{th} component is UP or DOWN, λ_i or μ_i is used in place of ρ_i

Monte Carlo Simulation

Composite system reliability evaluation with the use of cyber-physical interface matrix



Step 3: Find the minimum time, change the state of the corresponding component, and update the total time.

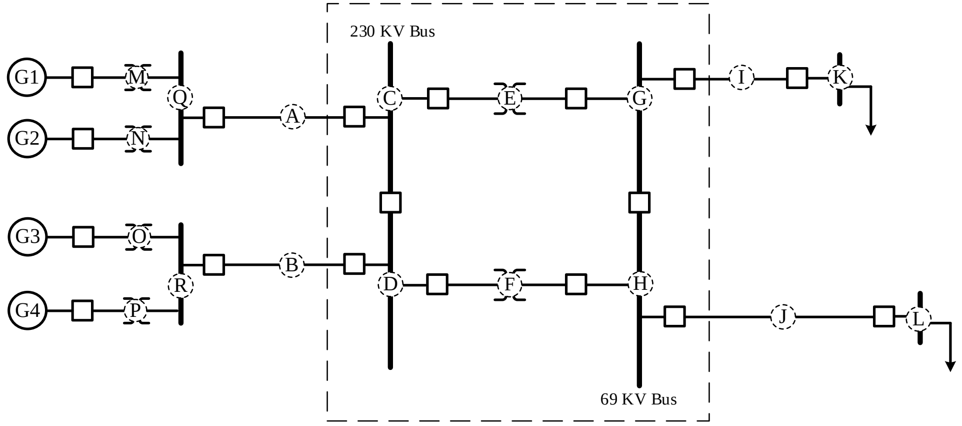
$$T_q = \min\{T_i\}, 1 \le i \le N$$

The next transition takes place by change of state of the q^{th} component. The total simulation time t is increased by T_q.

$$t = t + T_q$$

Monte Carlo Simulation

Composite system reliability evaluation with the use of cyber-physical interface matrix



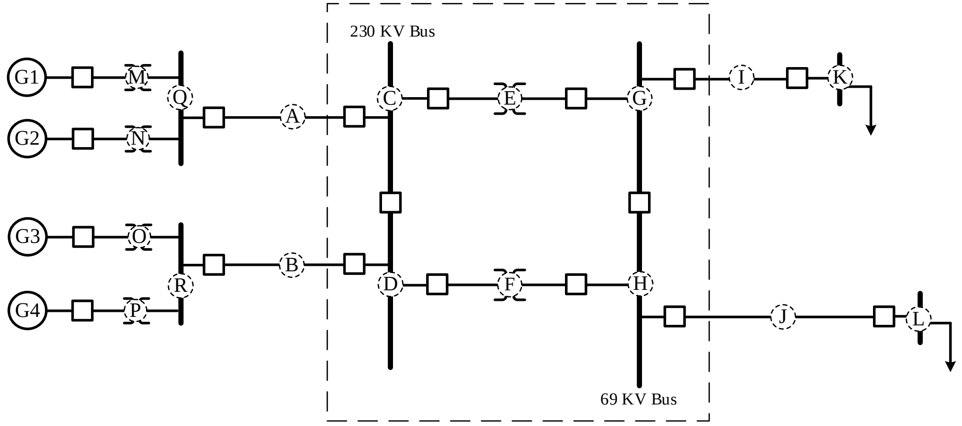
Step 4: Change the q^{th} component's state accordingly.

For each component i

$$T_i = T_i - T_q$$

Monte Carlo Simulation

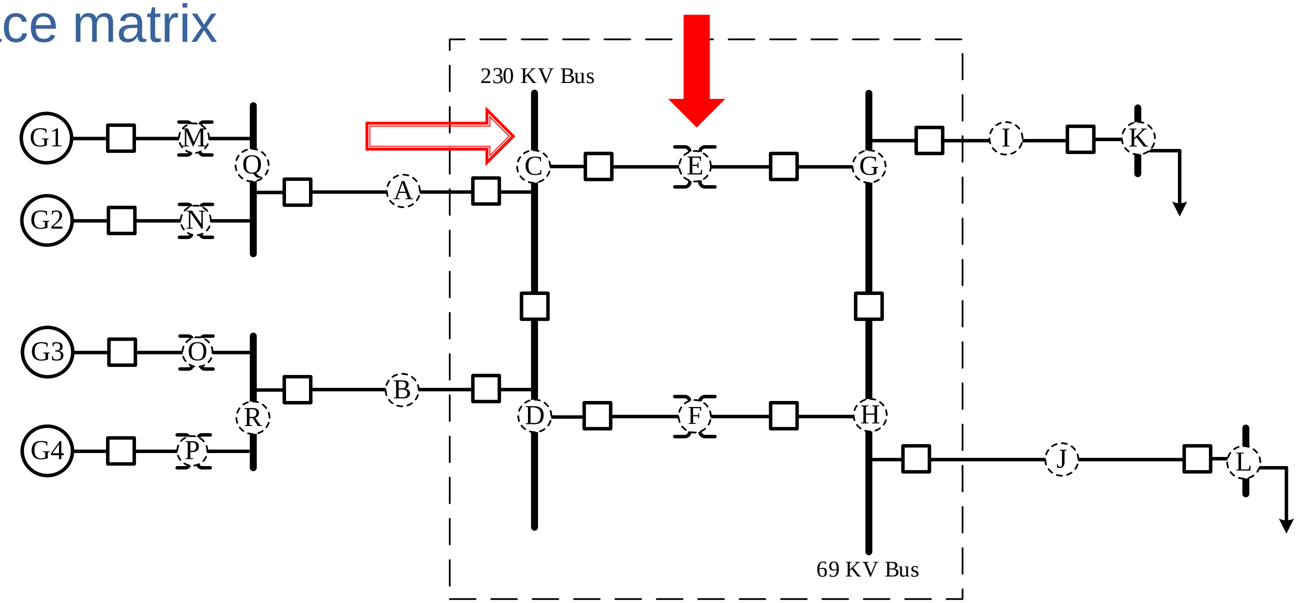
Composite system reliability evaluation with the use of cyber-physical interface matrix



Step 5: If the state of the q^{th} component transits from UP to DOWN, which means a primary fault occurs on this component, then the cyber-physical interface matrix is used to determine if there are some subsequent failures causing more components out of service due to the cyber part's malfunction.

Monte Carlo Simulation

Composite system reliability evaluation with the use of cyber-physical interface matrix

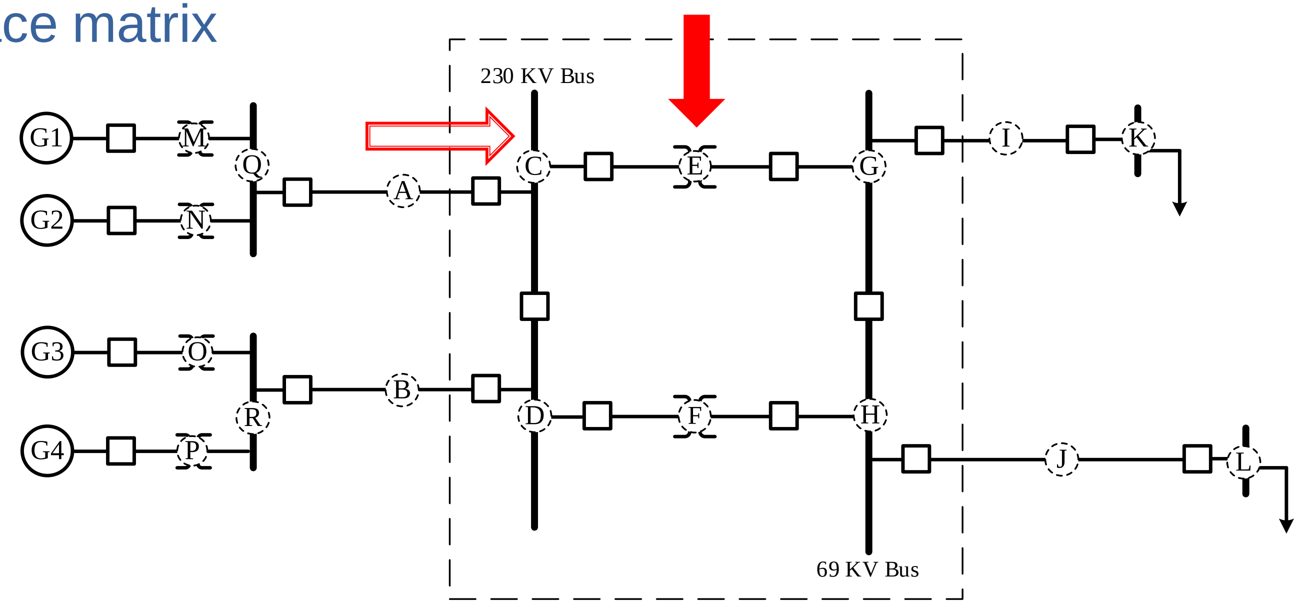


Draw another random decimal number y $(0 < y \leq 1)$

Line A	0.9969575	0.0000091	0.003[illegible]0334	0	……
……	……	……	……	……	**……**
Transformer E	0.9969423	0.0000091	0.0000152	0.0000152	**……**
……	**……**	**……**	**……**	**……**	**……**
Bus H	0.9969272	0.0000091	0.0000152	0.0000152	**……**

Monte Carlo Simulation

Composite system reliability evaluation with the use of cyber-physical interface matrix



How to determine the next transition time of Transformer E and Bus C?

$$T_i = -\frac{ln(z_i)}{\rho_i}$$

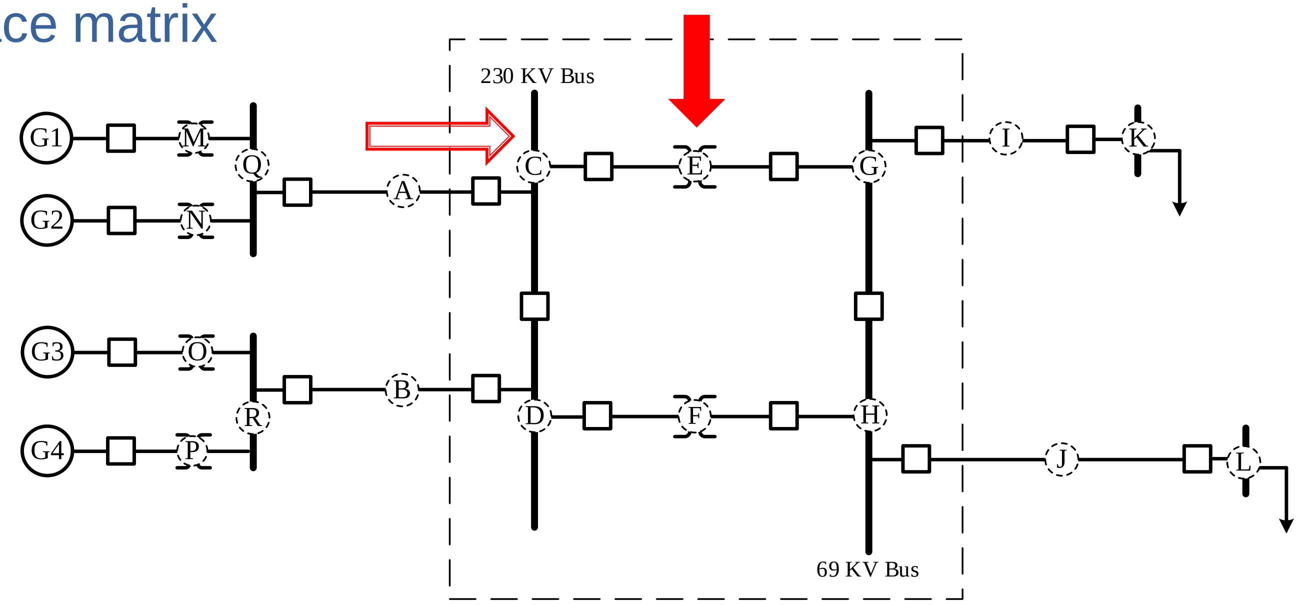
For Transformer E, use μ_i in place of ρ_i

For Bus C, use $\mu_{i,exp}$ in place of ρ_i

$\mu_{i,exp}$ is an expedited repair rate, called switching rate

Monte Carlo Simulation

Composite system reliability evaluation with the use of cyber-physical interface matrix



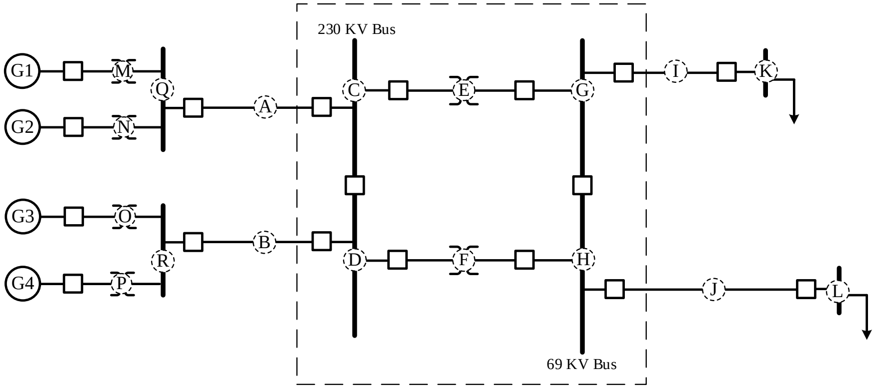
Step 6: Perform a network power flow analysis to assess system operation states. Update system-wide reliability indices.

Repeat steps 3–6 until convergence is achieved.

Monte Carlo Simulation

Composite system reliability evaluation with the use of cyber-physical interface matrix

When the simulation finishes, system-wide reliability indices can be obtained.



$$LOLP = \sum_{i=1}^{N_s} \frac{H_i * t_i}{t_{total}}$$

$$EENS = \sum_{i=1}^{N_s} \frac{R_i * t_i * 8760}{t_{total}}$$ (With the unit of $MWh/year$)

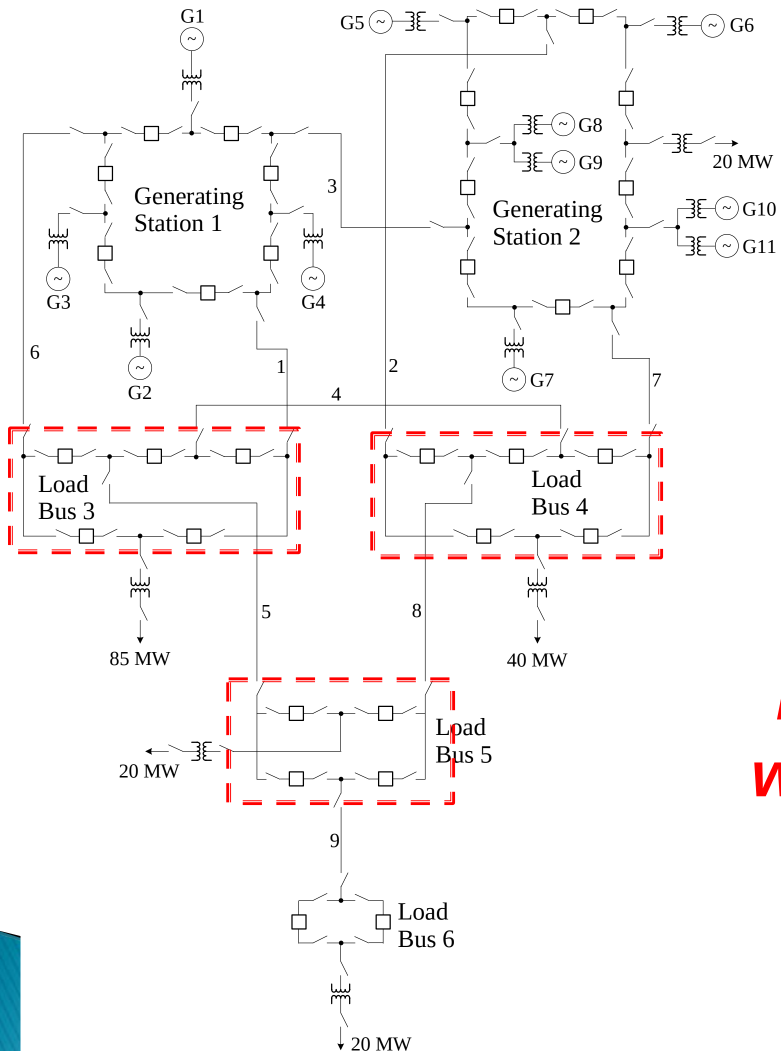
$$LOLE = LOLP * 8760$$

(With the unit of $hours/year$)

N_s	Total number of iterations simulated;
H_i	Equals 1 if load curtailment occurs in the i^{th} iteration; otherwise it equals 0;
t_i	Simulated time in the i^{th} iteration, with the unit of year;
t_{total}	Total simulated time, with the unit of year.
R_i	Load curtailment during the i^{th} iteration, with the unit of MW;

Illustrating the overall methodology on a standard test system

RBTS Test System



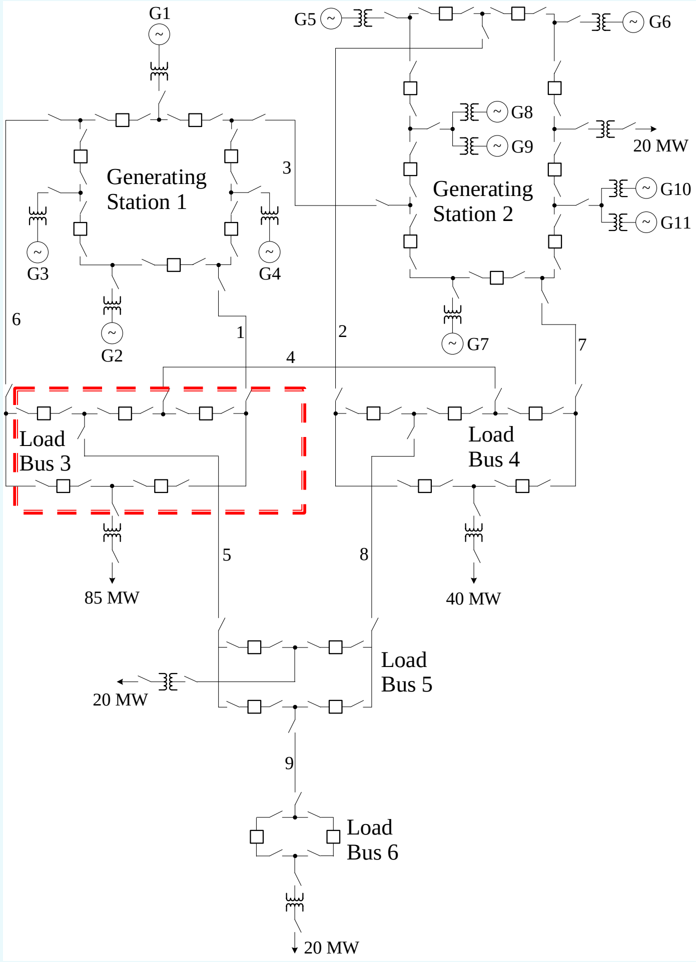
System Configuration

The size of this system is small to permit reasonable time for extension of cyber part and development of interface matrices.
But the configuration of this system is sufficiently detailed to reflect the actual features of a practical system

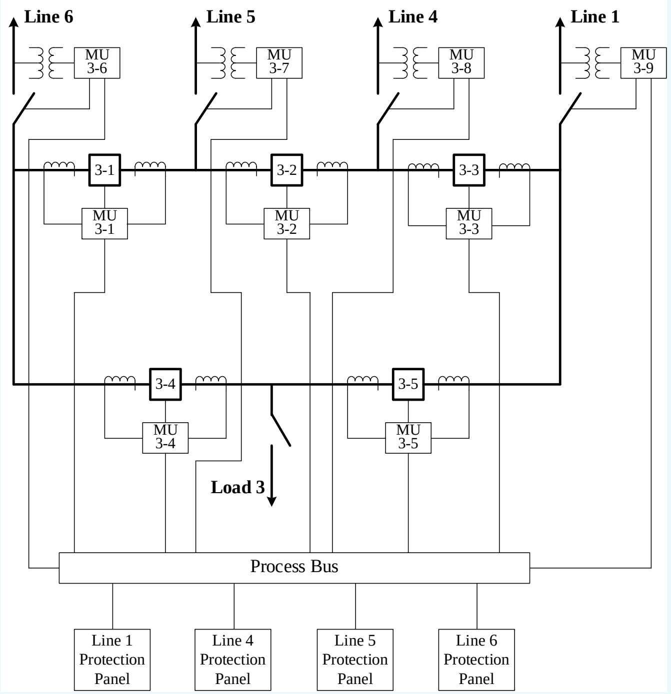
Buses 3–5 are extended with cyber configurations

System Configuration

Extend bus 3 of the RBTS Test System with substation protection configurations.



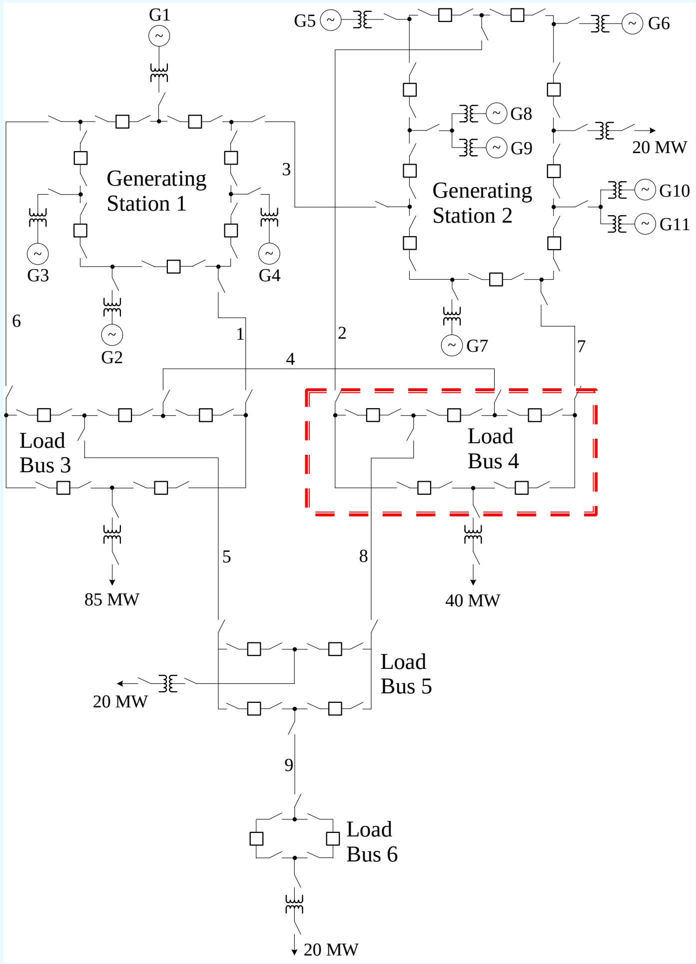
Physical part of the RBTS



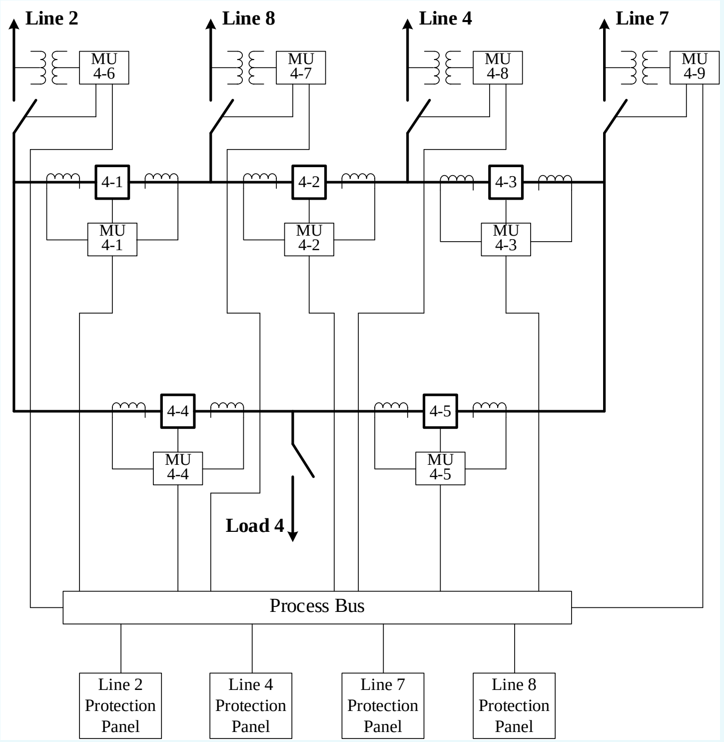
Extension with cyber part in **Bus 3**

System Configuration

Extend bus 4 of the RBTS with substation protection configurations.

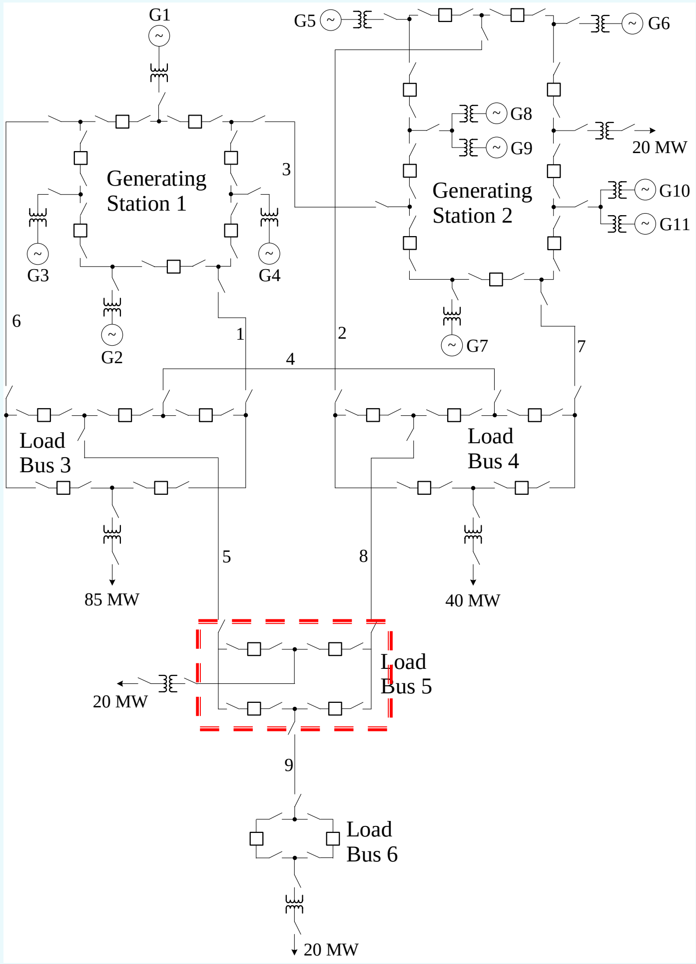


Physical part of the RBTS



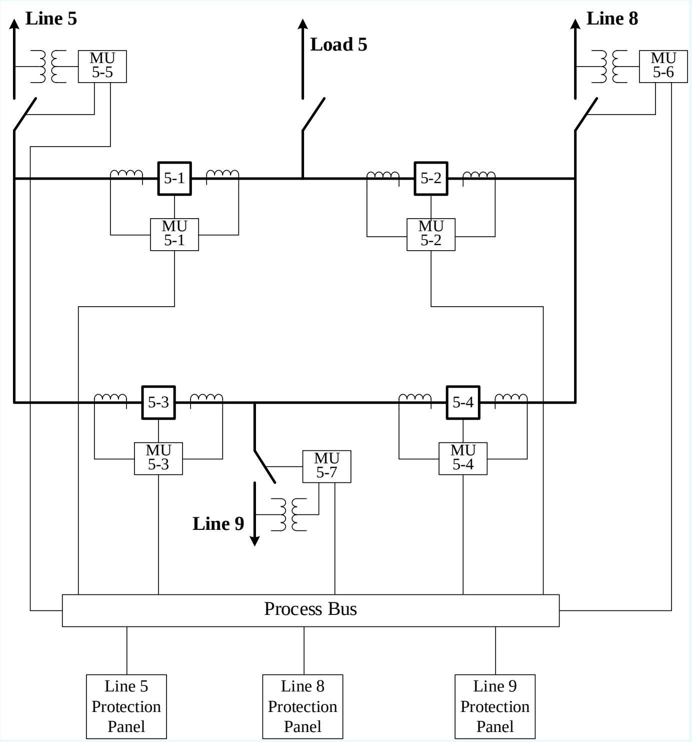
Extension with cyber part in **Bus 4**

System Configuration



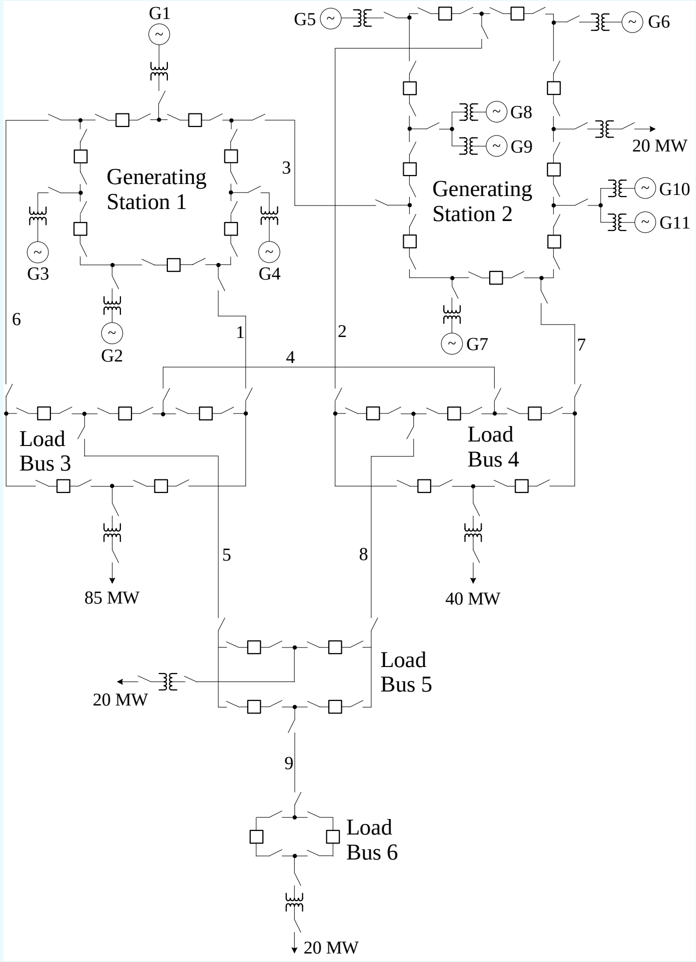
Physical part of the RBTS

Extend bus 5 of the RBTS with substation protection configurations.



Extension with cyber part in **Bus 5**

System Configuration



Physical part of the RBTS

Generation Variation

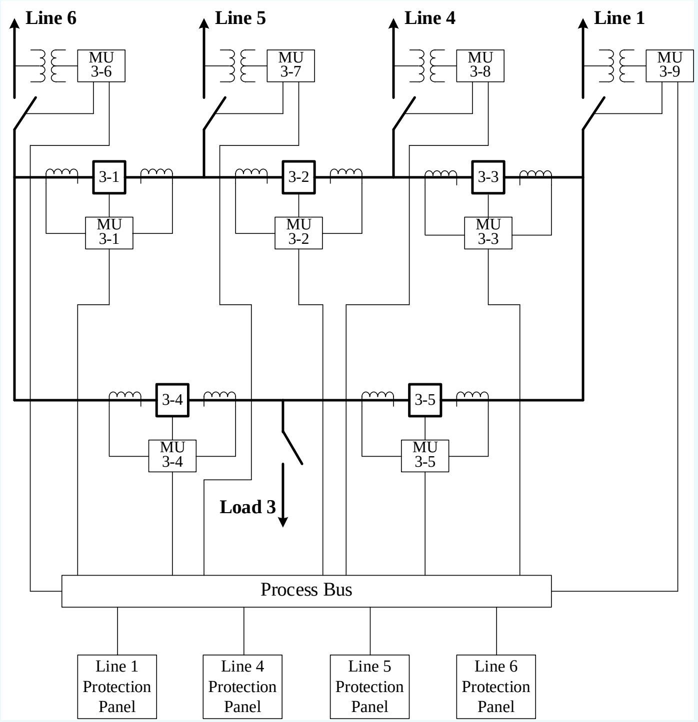
Unit No.	Bus	Rating (MW)	Failure Rate (/year)	MRT (hours)
1	1	40	6.0	45
2	1	40	6.0	45
3	1	10	4.0	45
4	1	20	5.0	45
5	2	5	2.0	45
6	2	5	2.0	45
7	2	40	3.0	60
8	2	20	2.4	55
9	2	20	2.4	55
10	2	20	2.4	55
11	2	20	2.4	55

Load Variation

The hourly load profile is created based on the information in Tables 1, 2, and 3 of the IEEE Reliability Test System*.

*IEEE Committee Report, “IEEE reliability test system,” *IEEE Trans. Power App. and Syst.*, vol. PAS-98, no. 6, pp. 2047–2054, Nov./Dec. 1979.

Stage 1: Substation Level Analysis



$$\begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,n} \\ p_{2,1} & p_{2,2} & & p_{2,n} \\ \vdots & & \ddots & \vdots \\ p_{m,1} & p_{m,2} & \cdots & p_{m,n} \end{bmatrix}$$

Analyze the cyber failure modes and consequent events and obtain the Cyber-Physical Interface Matrices (CPIM) for Buses 3-5.

Stage 1: Substation Level Analysis

Results: The CPIM and CEM of Bus 3

The Cyber-Physical Interface Matrix (CPIM) of Bus 3

Fault Location	Probabilities				
Line 1	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112
Line 4	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112
Line 5	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112
Line 6	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112

The Consequent Event Matrix (CEM) of Bus 3

Fault Location	Events				
Line 1	100000000000	100111000000	100100000000	100000000100	100100000100
Line 4	000100000000	100111000000	000110000000	100100000000	100110000000
Line 5	000010000000	100111000000	000011000000	000110000000	000111000000
Line 6	000001000000	100111000000	000001000100	000011000000	000011000100

Stage 1: Substation Level Analysis

Results: The CPIM and CEM of Bus 4

The Cyber-Physical Interface Matrix (CPIM) of Bus 4

Fault Location	Probabilities				
Line 2	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112
Line 4	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112
Line 7	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112
Line 8	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112

The Consequent Event Matrix (CEM) of Bus 4

Fault Location	Events				
Line 2	010000000000	010100110000	010000000010	010000010000	010000010010
Line 4	000100000000	010100110000	000100010000	000100100000	000100110000
Line 7	000000100000	010100110000	000100100000	000000100010	000100100010
Line 8	000000010000	010100110000	010000010000	000100010000	010100010000

Stage 1: Substation Level Analysis

Results: The CPIM and CEM of Bus 5

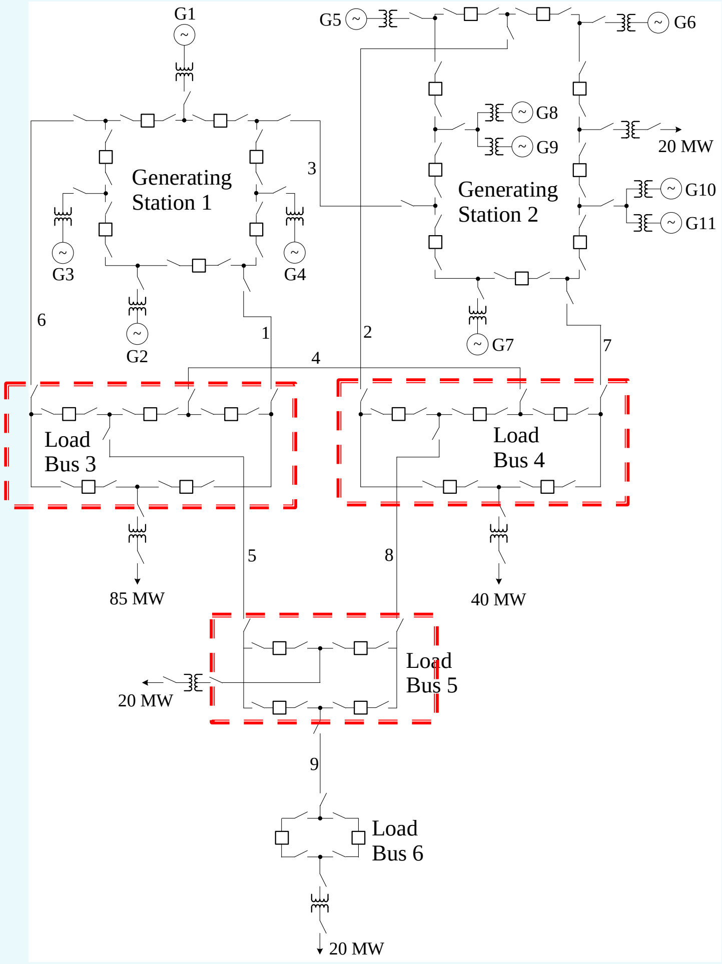
The Cyber-Physical Interface Matrix (CPIM) of Bus 5

Fault Location	Probabilities				
Line 5	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112
Line 8	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112
Line 9	0.996899850569	0.000009132337	0.000027312491	0.000027312491	0.003036392112

The Consequent Event Matrix (CEM) of Bus 5

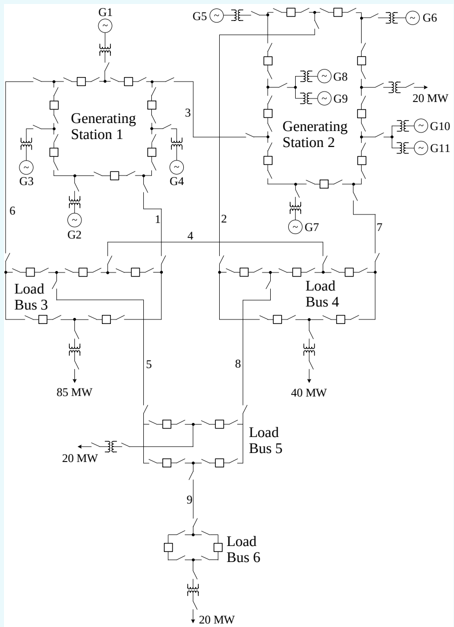
Fault Location	Events				
Line 5	000010000000	000010011000	000010001000	000010000001	000010001001
Line 8	000000010000	000010011000	000000010001	000000011000	000000011001
Line 9	000000001000	000010011000	000000011000	000010001000	000010011000

Stage 2: Composite System Level Analysis



Utilize the results of the interface matrices, perform a Monte-Carlo simulation for the composite system, and obtain numerical results of system-wide reliability indices.

Stage 2: Composite System Level Analysis



Objective: $y = Min \sum_{i=1}^{N_b} C_i$

subject to:

$$\hat{B}\theta + G + C = L$$
$$G \leq G^{max}$$
$$C \leq L$$
$$DA\theta \leq F^{max}$$
$$-DA\theta \leq F^{max}$$
$$G, C \geq 0$$
$$\theta_1 = 0$$
$$\theta_{2 \ldots N_b} \text{ unrestricted}$$

Variables: θ, G, and C

Total number of variables: $3N_b$

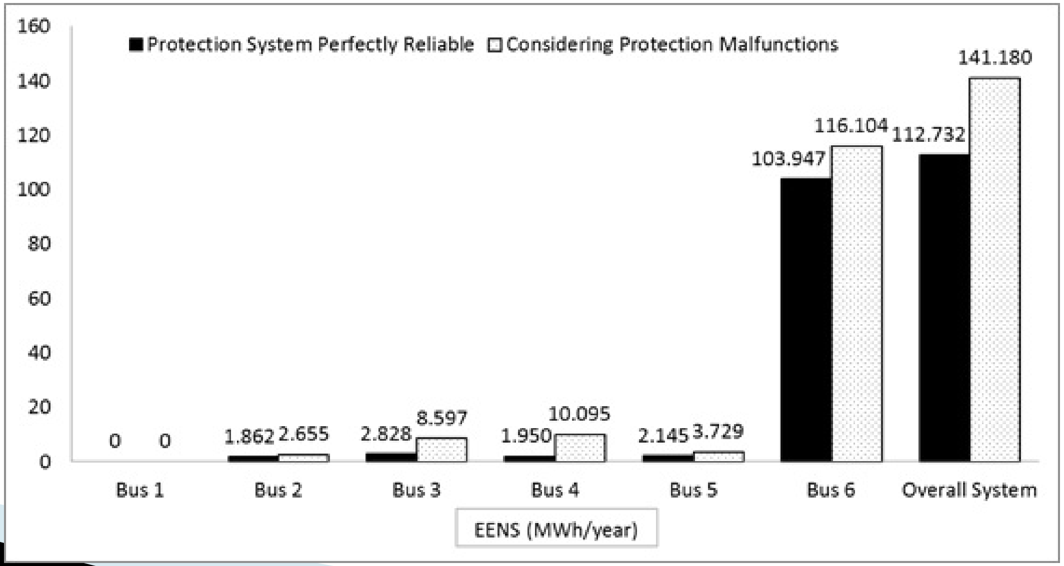
N_b	Number of buses
C	$N_b \times 1$ vector of bus load curtailments
C_i	Load curtailment at bus i
$\hat{B}$	$N_b \times N_b$ augmented node susceptance matrix
G	$N_b \times 1$ vector of bus actual generating power
G^{max}	$N_b \times 1$ vector of bus maximum generating availability
L	$N_b \times 1$ vector of bus loads
D	$N_t \times N_t$ diagonal matrix of transmission line susceptances, with N_t the number of transmission lines
A	$N_t \times N_b$ line-bus incidence matrix
θ	$N_b \times 1$ vector of bus voltage angles
F^{max}	$N_t \times 1$ vector of transmission line power flow capacities

Stage 2: Composite System Level Analysis

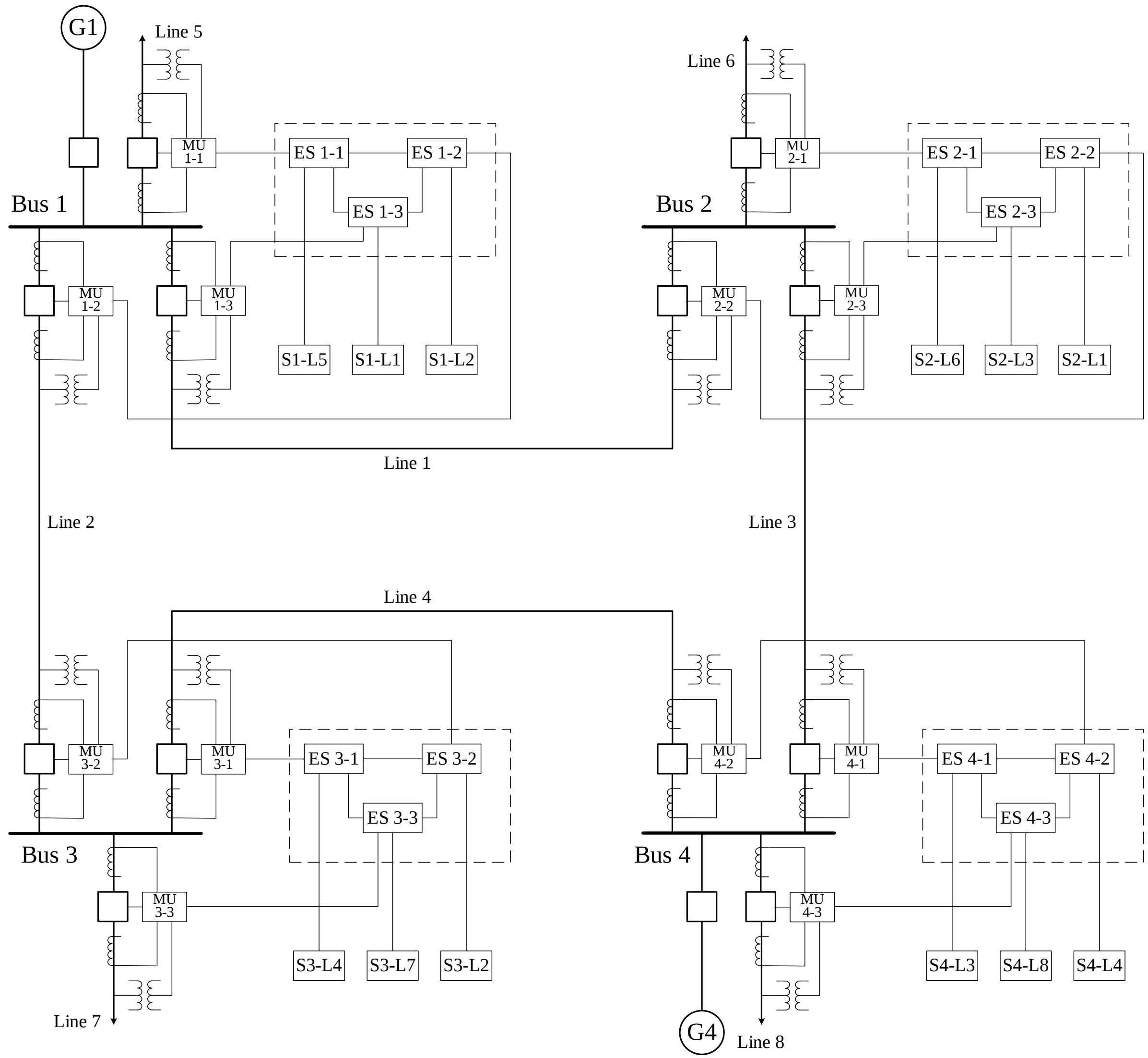
Brief Results

Impact on Expected Energy Not Served (EENS)

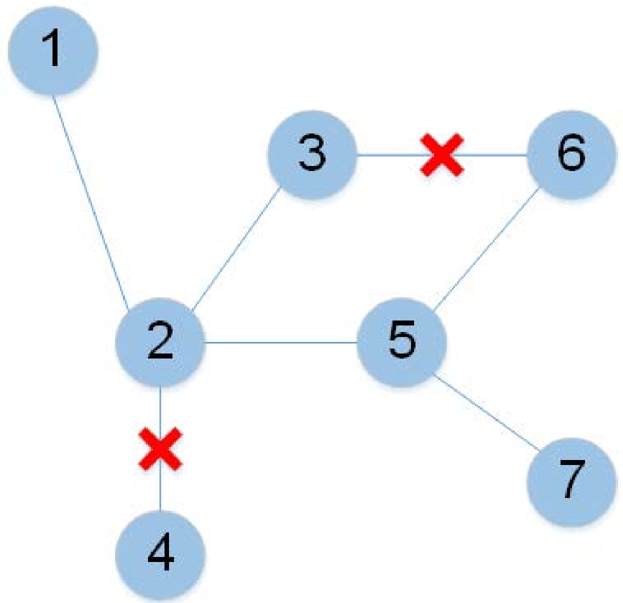
	EENS (MWh/year)		Δ
	If protection systems are perfectly reliable	Considering protection malfunctions	
Bus 1	0	0	N/A
Bus 2	1.862	2.655	42.59%
Bus 3	2.828	8.597	204.00%
Bus 4	1.950	10.095	417.69%
Bus 5	2.145	3.729	73.85%
Bus 6	103.947	116.104	11.70%
Overall System	112.732	141.180	25.24%



Modeling Cyber Link Failures



Modeling Cyber Link Failures



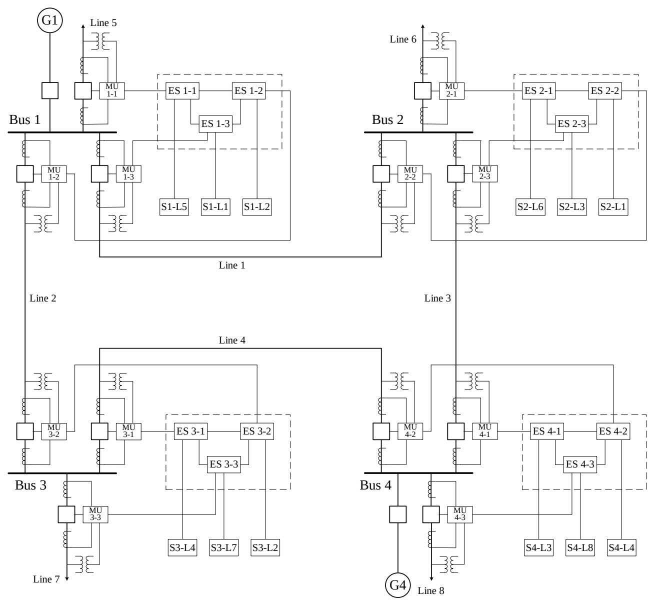
Two types of cyber link failures:

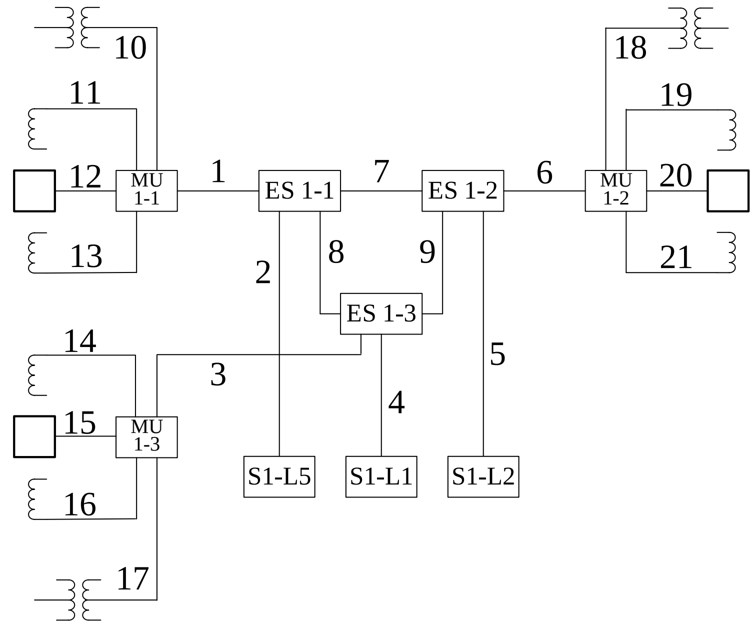
(a) A link is unavailable due to packet delay resulting from traffic congestion or queue failure;

(b) A link is physically damaged.

Failure type (b) is relatively rare and thus only failure type (a) is considered in this research

Modeling Cyber Link Failures





Reliability Data for Components

Component	Failure Rate (/year)	Mean Repair Time (h)
Circuit Breaker	0.01	8
Merging Unit	0.02	8
Ethernet Switch	0.01	8
Line Protection Panel	0.02	8

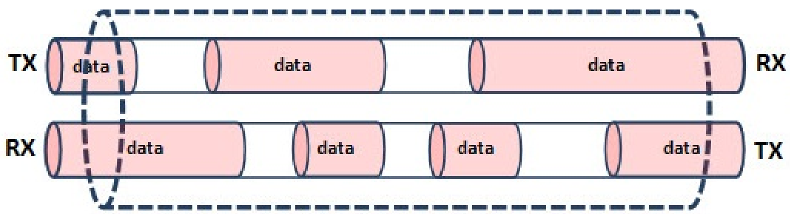
Cyber Component Names and Meanings

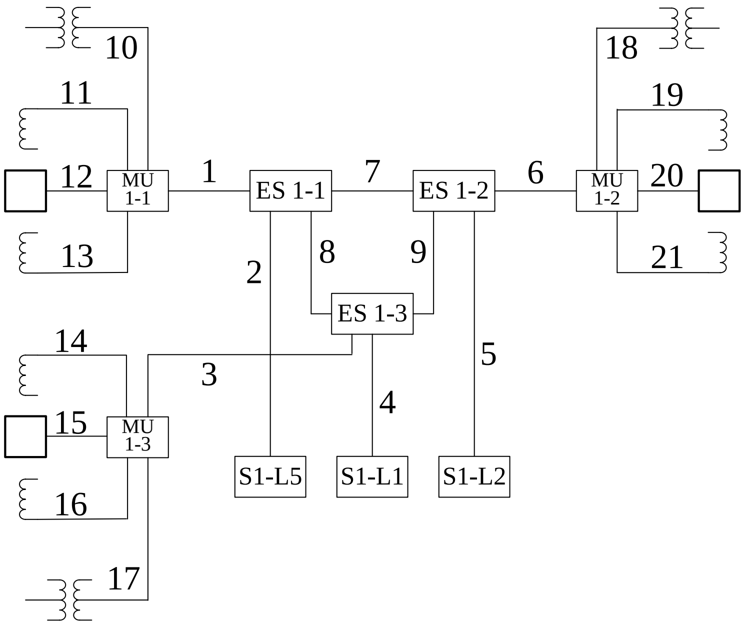
Component Name	Meaning
MU 1-1	Merging Unit 1 at Substation 1
MU 1-2	Merging Unit 2 at Substation 1
MU 1-3	Merging Unit 3 at Substation 1
ES 1-1	Ethernet Switch 1 at Substation 1
ES 1-2	Ethernet Switch 2 at Substation 1
ES 1-3	Ethernet Switch 3 at Substation 1
S1-L5	Line 5 Protection Panel at Substation 1
S1-L1	Line 1 Protection Panel at Substation 1
S1-L2	Line 2 Protection Panel at Substation 1

Modeling Cyber Link Failures

Cyber Component Names and Meanings

Component Name	Meaning
MU 1-1	Merging Unit 1 at Substation 1
MU 1-2	Merging Unit 2 at Substation 1
MU 1-3	Merging Unit 3 at Substation 1
ES 1-1	Ethernet Switch 1 at Substation 1
ES 1-2	Ethernet Switch 2 at Substation 1
ES 1-3	Ethernet Switch 3 at Substation 1
S1-L5	Line 5 Protection Panel at Substation 1
S1-L1	Line 1 Protection Panel at Substation 1
S1-L2	Line 2 Protection Panel at Substation 1





For the link i, the time it takes for a packet to travel in the forward direction is a random variable denoted by $t_{i.1}$

For the reverse direction, the random time is denoted by $t_{i.2}$

For example:

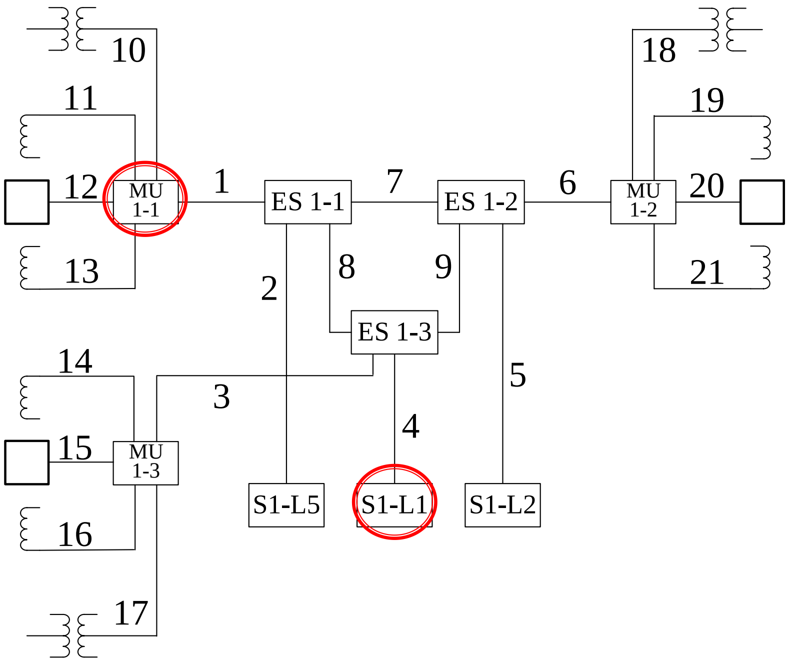
Consider Link 7, the time it takes for a packet to travel from ES 1-1 to ES 1-2 is denoted by $t_{7.1}$

From ES 1-2 to ES 1-1, the time is denoted by $t_{7.2}$

Modeling Cyber Link Failures

Cyber Component Names and Meanings

Component Name	Meaning
MU 1-1	Merging Unit 1 at Substation 1
MU 1-2	Merging Unit 2 at Substation 1
MU 1-3	Merging Unit 3 at Substation 1
ES 1-1	Ethernet Switch 1 at Substation 1
ES 1-2	Ethernet Switch 2 at Substation 1
ES 1-3	Ethernet Switch 3 at Substation 1
S1-L5	Line 5 Protection Panel at Substation 1
S1-L1	Line 1 Protection Panel at Substation 1
S1-L2	Line 2 Protection Panel at Substation 1

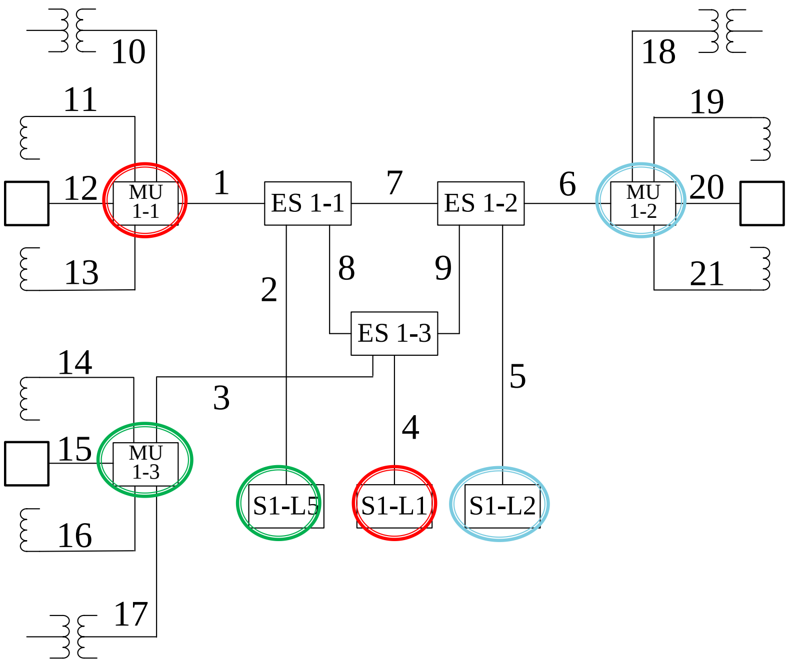


Consider the communication from MU 1-1 to S1-L1. There are two possible paths: 1-8-4 and 1-7-9-4.

$$p_{fail} = \Pr[(t_{1.1} + t_{8.1} + t_{4.1} > T_{tsd})\ and\ (t_{1.1} + t_{7.1} + t_{9.1} + t_{4.1} > T_{tsd})]$$

where T_{tsd} is a predefined threshold delay value for the two paths.

Modeling Cyber Link Failures

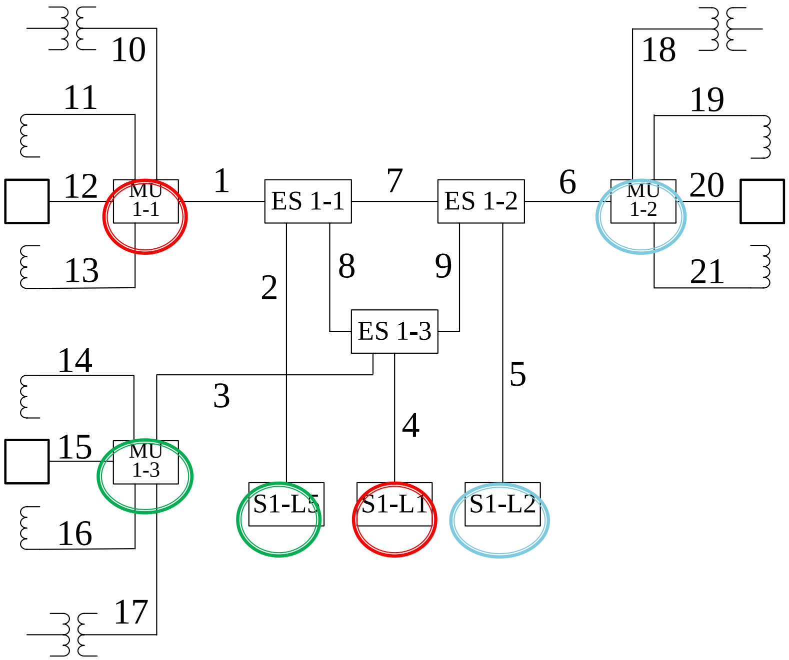


From MU 1-1 to S1-L1

$$p_{fail} = \Pr[(t_{1.1} + t_{8.1} + t_{4.1} > T_{tsd})\ and\ (t_{1.1} + t_{7.1} + t_{9.1} + t_{4.1} > T_{tsd})]$$

Similarly, with any two components specified as the two ends of a communication path, the path failure probability can be computed from the cyber link level parameters

Modeling Cyber Link Failures

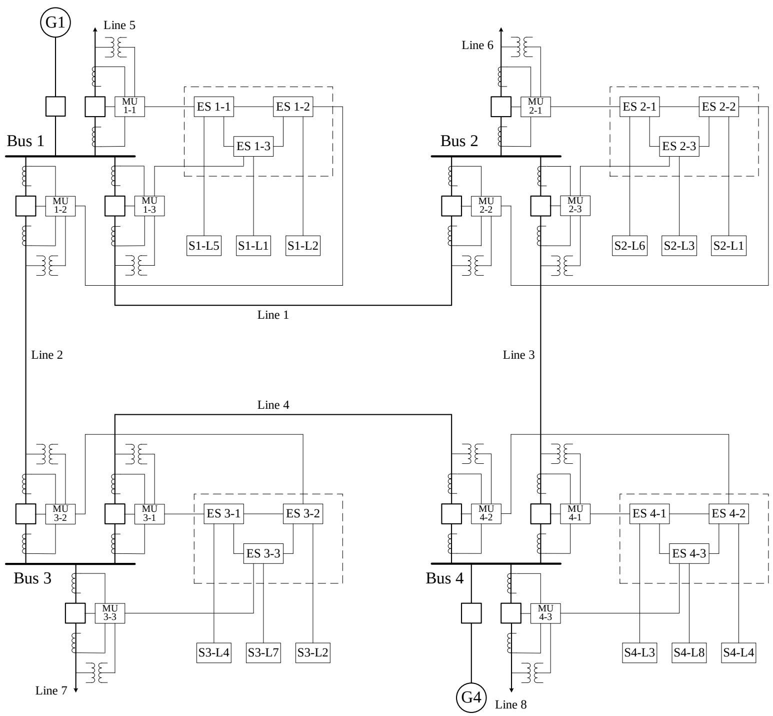


The detailed procedures are based on queueing theory and are beyond the scope of this research. These probabilities can be assumed directly at the path level.

From	To	Forward Path Failure Probability	Reverse Path Failure Probability
MU 1-1	S1-L5	0.002	0.002
MU 1-1	S1-L1	0.001	0.001
MU 1-1	S1-L2	0.001	0.001
MU 1-2	S1-L5	0.001	0.001
MU 1-2	S1-L1	0.001	0.001
MU 1-2	S1-L2	0.002	0.002
MU 1-3	S1-L5	0.001	0.001
MU 1-3	S1-L1	0.002	0.002
MU 1-3	S1-L2	0.001	0.001

Modeling Cyber Link Failures

Results



The Cyber-Physical Interface Matrix

Primary Fault Location	Probabilities of Consequent Events			
Line 1	0.9919152	0.0040342	0.0040342	0.0000164
Line 2	0.9919152	0.0040342	0.0040342	0.0000164
Line 3	0.9919152	0.0040342	0.0040342	0.0000164
Line 4	0.9919152	0.0040342	0.0040342	0.0000164
Line 5	0.9959494	0.0040506	0	0
Line 6	0.9959494	0.0040506	0	0
Line 7	0.9959494	0.0040506	0	0
Line 8	0.9959494	0.0040506	0	0

The Consequent Event Matrix

Primary Fault Location	Consequent Events			
Line 1	10000000	11001000	10100100	11101100
Line 2	01000000	11001000	01010010	11011010
Line 3	00100000	10100100	00110001	10110101
Line 4	00010000	01010010	00110001	01110011
Line 5	00001000	11001000	00000000	00000000
Line 6	00000100	10100100	00000000	00000000
Line 7	00000010	01010010	00000000	00000000
Line 8	00000001	00110001	00000000	00000000

Comments on Scalability

Stage 1: Substation Level Analysis

Analysis at this stage can be performed locally at each substation and the computations can be performed **offline**.

Stage 2: Composite System Level Analysis

The results of CPIMs and CEMs can be directly utilized. Monte-Carlo simulation performed in this stage is generic and applicable for large power systems.

The CPIM decouples the 2 stages of analysis, making the overall analysis more tractable.

Further work

- Cyber-Physical Interactions Modeling
  - This is only starting point
  - More detailed models need to be developed.
  - We need to consider inter-substation interactions
  - Consider the interaction of physical on the cyber as well
  - More automated analysis at the substation level.

Further Work

- Computational Methods Development
  - Generally non-sequential Monte Carlo Simulation is preferred as a more efficient method of for reliability evaluation.
  - Several variance reduction techniques like importance sampling have been developed to make it even faster, especially those incorporating the concept of cross-entropy.
  - The efficiency of non-sequential MCS is based on the assumption of independence between the components, although limited dependence can be accommodated.

Further Work

- Because of interdependence introduced by cyber part it becomes difficult to use non-sequential MC and the associated variance reduction techniques. So we have used sequential MCS.
- We have also proposed a non-sequential MCS technique to solve this problem but more work is needed in this direction.

Test System

- IEEE RTS – Reliability Test System has served as a resource for the researchers and developers to test their algorithms and compare their results with others.
- Additional information about distribution has since been added.
- This test system does not have information on the related cyber part.
- A taskforce under the Reliability, Risk and Probability Applications Subcommittee (RRPA) is investigating adding configurations and data on the cyber part.

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Questions?

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