June 29, 2022

Courtney Otani, Idaho National Laboratory

Kurt G. Vedros, Idaho National Laboratory

Electrical Substation Configuration Effect on Substation Reliability



Motivation and Scope

I ogond.

Dravious Work [2]

- Institute of Electrical and Electronics Engineers (IEEE) recommends traditional probabilistic risk analysis (PRA) based on availability of individual components for designing reliable industrial and commercial power systems [1]
- PRA based studies only done on differences in configuration- no variation in number of inputs/circuits.

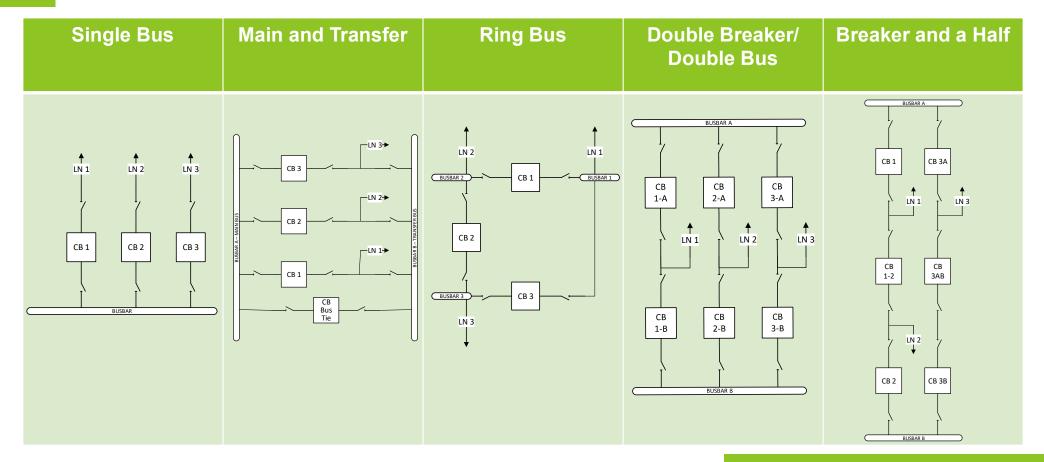
V Now Work

Legend. O Fievi	005 000		X		VUIK			
No. Lines Configuration	1	2	3	4	5	6	7	8
Single Bus	Х	X	Х	0	Х	X	X	X
Breaker and a Half	Х	X	X	0	Х	X	X	X
Ring	X	X	X	0	Х	X	X	X
Main and Transfer	Х	X	Х	0	Х	X	X	X
Double Breaker- Double Bus	X	X	X	0	X	X	X	Х

Methodology

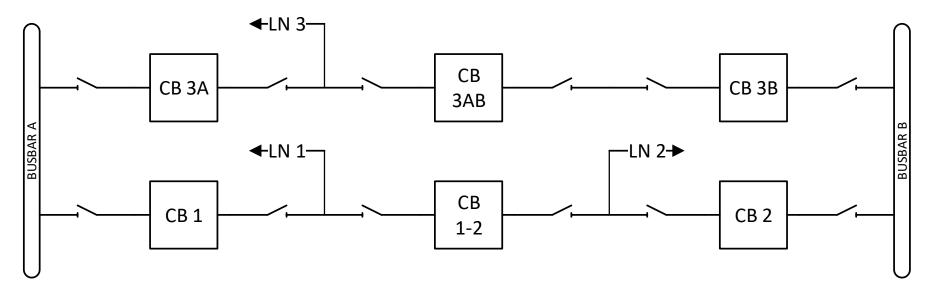
- 1. Obtain <u>bus configuration</u>
 - One line diagram of bus
- 2. Define failure criteria
 - Criteria that constitutes a failed bus
- 3. Define failure states and conditions
 - Detail combination of breakers, control panels, and busbars required to meet the failure criteria
- 4. Create logic statements and fault trees
 From failure states
- 5. Evaluate and rank results of logic model
 - Failure probability and unavailability

Bus Configurations Considered



Bus Configuration

Breaker and a Half, three lines



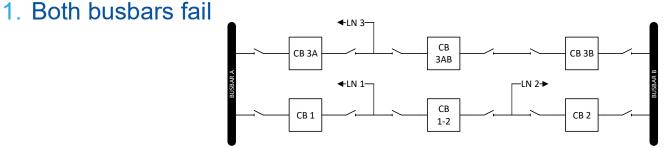
*Isolation switches not considered

Failure Criteria

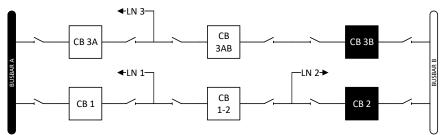
Bus cannot transmit any electrical signal

* Consistent for all substation configurations

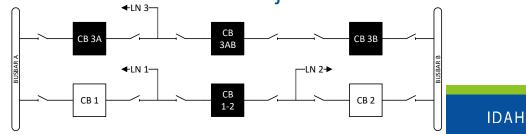
Failure States



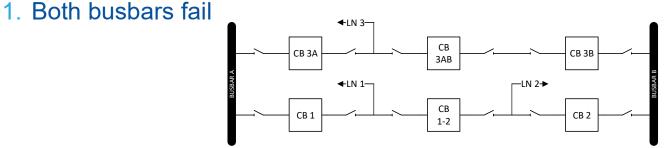
2. Bus fault with failed associated circuit breakers



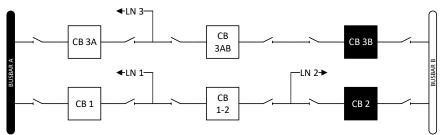
3. All middle breakers fail and one breaker adjacent to each busbar fails.



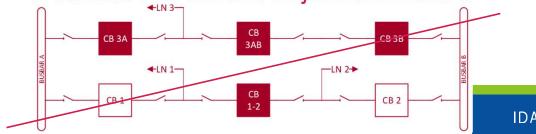
Failure States

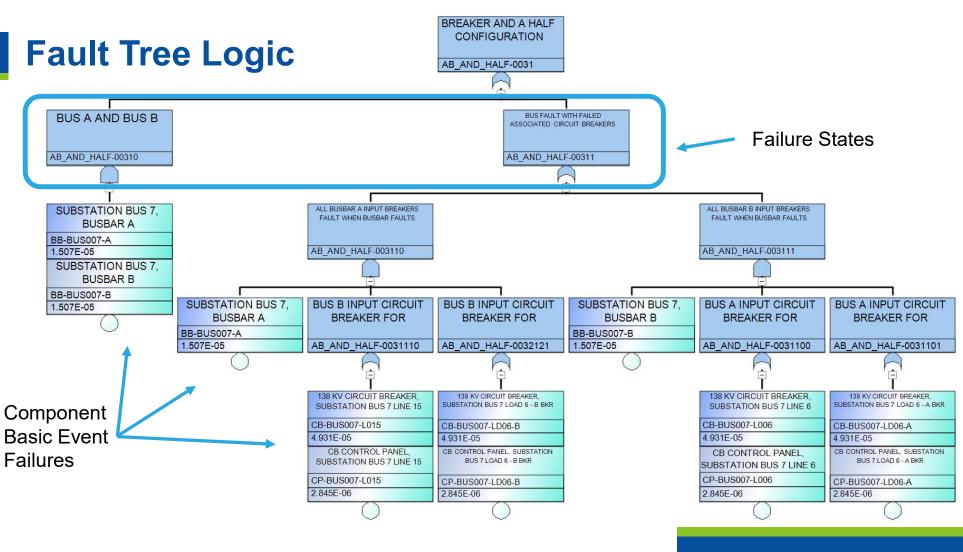


2. Bus fault with failed associated circuit breakers



3. All middle breakers fail and one breaker adjacent to each busbar fails.





IDAHO NATIONAL LABORATORY

Cut Set Results

								- 500
3	5	7	9	11	13	15	17	- 450
								- 400
2	2	11	10	27		125	250	- 350
3	5	11	10	37	66	135	258	- 300
								- 250
5	5	9	9	17	17	33	33	- 200
								- 150
								- 100
5	9	17	33	65	129	257	513	- 50
1	2	3	4 Number	5 of Inputs	6	7	8	
	3	3 5 5 5 5 9	3 5 11 3 5 9 5 5 9 5 9 17	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	3 5 11 10 37 5 5 9 9 17 5 9 17 33 65	3 5 11 10 37 66 5 5 9 9 17 17 5 9 17 33 65 129 1 2 3 4 5 6	3 5 11 10 37 66 135 5 5 9 9 17 17 33 5 9 17 33 65 129 257 1 2 3 4 5 6 7	3 5 11 10 37 66 135 258 5 5 9 9 17 17 33 33 5 9 17 33 65 129 257 513 1 2 3 4 5 6 7 8

									10 ⁻⁴
Single or Main and Transfer	6.7e-05	0.00012	0.00017	0.00022	0.00028	0.00033	0.00038	0.00043	10 ⁻⁶
Ring Bus Sing Bus Breaker and a Half	6.7e-05	0.00012	6.8e-10	4.5e-10	1.7e-14	6.9e-15	3.6e-19	1.0e-19	10 ⁻⁸
Breaker and a Half	1.8e-09	1.8e-09	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	10^{-12} 10^{-14}
Double Breaker/Double Bus	1.8e-09	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	10 ⁻¹⁶
	1	2	3	4 Number	5 of Inputs	6	7	8	

IDAHO NATIONAL LABORATORY

Bus Configuration

Continual increase in failure rate

Single or Main and Transfer	6.7e-05	0.00012	0.00017	0.00022	0.00028	0.00033	0.00038	0.00043	
Ring Bus Outfiguration Breaker and a Half	6.7e-05	0.00012	6.8e-10	4.5e-10	1.7e-14	6.9e-15	3.6e-19	1.0e-19	uner hunner hunner m
Sing Breaker and a Half	1.8e-09	1.8e-09	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	nn - Imne - Imne - Imne
Double Breaker/Double Bus	1.8e-09	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	
	1	2	3	4 Number	5 of Inputs	6	7	8	

 10^{-4} Single or Main and Transfer 6.7e-05 0.00043 0.00012 0.00017 0.00022 0.00028 0.00033 0.00038 10^{-6} 10^{-8} Ring Bus 6.7e-05 0.00012 6.8e-10 4.5e-10 6.9e-15 1.7e-14 3.6e-19 1.0e-19 10^{-10} e-04 10⁻¹² Breaker and a Half 1.8e-09 1.8e-09 2.3e-10 2.3e-10 2.3e-10 2.3e-10 2.3e-10 2.3e-10 10⁻¹⁴ 10⁻¹⁶ Double Breaker/Double Bus 1.8e-09 2.3e-10 2.3e-10 2.3e-10 2.3e-10 2.3e-10 2.3e-10 2.3e-10 10⁻¹⁸ 2 3 4 5 6 7 8 1 Number of Inputs

Multiple order of magnitude decreases for the Ring Bus

		Identio	car compo		$e up \rightarrow ue$		lie rate pa			
Single	or Main and Transfer	6.7e-05	0.00012	0.00017	0.00022	0.00028	0.00033	0.00038	0.00043	10 ⁻⁴ 10 ⁻⁶
Bus Configuration	Ring Bus	6.7e-05	0.00012	6.8e-10	4.5e-10	1.7e-14	6.9e-15	3.6e-19	1.0e-19	10 ⁻⁸ 10 ⁻¹⁰
Bus Con	Breaker and a Half	1.8e-09	1.8e-09	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	10 ⁻¹²
Double	Breaker/Double Bus	1.8e-09	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	10 ⁻¹⁶
		1	2	3	4 Number	5 of Inputs	6	7	8	

Identical component make up \rightarrow Identical failure rate pairs

IDAHO NATIONAL LABORATORY

Bus Configuration

Single c	or Main and Transfer	6.7e-05	0.00012	0.00017	0.00022	0.00028	0.00033	0.00038	0.00043	10 ⁻⁴ 10 ⁻⁶
Bus Configuration	Ring Bus	6.7e-05	0.00012	6.8e-10	4.5e-10	1.7e-14	6.9e-15	3.6e-19	1.0e-19	10 ⁻⁸ 10 ⁻¹⁰
Bus Conf	Breaker and a Half	1.8e-09	1.8e-09	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	10 ⁻¹² 10 ⁻¹⁴
Double	Breaker/Double Bus	1.8e-09	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	2.3e-10	10 ⁻¹⁶
	·	1	2	3	4 Number	5 of Inputs	6	7	8	

Plateau driven by reliability of busbar pair

IDAHO NATIONAL LABORATORY

Bus Configuration

Ranking of <u>Reliability</u> based on Number of Inputs

Switch in most reliable from DBB/BAH and RNG when increase from four to five inputs

					Number	of Inputs			
		1	2	3	4	5	6	7	8
ſ	High	1. DBB	1. DBB	1. DBB	1. DBB 🗕	🔶 RNG	1. RNG	1. RNG	1. RNG
	1	1. BAH	2. BAH	1. BAH	1. BAH	2. DBB	2. DBB	2. DBB	2. DBB
l	\downarrow	3. RNG	3. RNG	3. RNG	3. RNG	2. BAH	2. BAH	2. BAH	2. BAH
	Low	4. S/MT	4. S/MT	4. S/MT	4. S/MT	4. S/MT	4. S/MT	4. S/MT	4. S/MT

S/MT	Single and Main and Transfer	BAH	Breaker and a Half
RNG	Ring Bus	DBB	Double Breaker/Double Bus

Ranking of <u>Reliability</u> based on Number of Inputs

Single and Main and Transfer configuration are consistently the least reliable

				Number	of Inputs			
	1	2	3	4	5	6	7	8
High	1. DBB	1. DBB	1. DBB	1. DBB	1. RNG	1. RNG	1. RNG	1. RNG
-	1. BAH	2. BAH	1. BAH	1. BAH	2. DBB	2. DBB	2. DBB	2. DBB
Ļ	3. RNG	3. RNG	3. RNG	3. RNG	2. BAH	2. BAH	2. BAH	2. BAH
Low	4. S/MT	4. S/MT	4. S/MT	4. S/MT				

S/MT	Single or Main and Transfer	BAH	Breaker and a Half
RNG	Ring Bus	DBB	Double Breaker/Double Bus

Conclusions

- Reliability of the substation generally corresponds to the number of inputs
 - Single and Main and Transfer configurations have a positive correlation
 - All other configurations examined have an inverse correlation
- Double Breaker/Double bus, Breaker and a half, and Ring bus configurations are the most reliable
 - Double Breaker/Double Bus and Breaker and a half for one to four inputs
 - Ring bus for five or greater inputs
- This builds a foundation for quantified understanding of reliability in two parameters, configuration and number of inputs
- Adding cost as a parameter would enhance usefulness of data
 - Cut set numbers are a general indicator
 - Capital costs
 - Operation and maintenance costs

References

[1] 2007. "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems." IEEE Std 493-2007, Institute of Electrical and Electronics Engineers. <u>https://doi.org/10.1109/IEEESTD.2007.380668</u>.

[2] Tsao, Teng-Fa and Chang, Hong-Chan. 2003. "Composite Reliability Evaluation Model for Different Types of Distribution Systems." IEEE Transactions on Power Systems, 19 (2): 924–930. <u>https://doi.org/10.1109/TPWRS.2003.811174</u>.

Acknowledgements

This work has been supported by the Department of Energy - Office of Electricity Advanced Grid Research and Development program under AOP #TCF-21-24936.

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

$\mathsf{W} \; \mathsf{W} \; \mathsf{W} \; \mathsf{N} \; \mathsf{I} \; \mathsf{N} \; \mathsf{L} \; . \; \mathsf{G} \; \mathsf{O} \; \mathsf{V}$

4 input Cost Study

Configuration	Multiplied value	Failure rate [/hr]	Approximate relative cost comparison*
Breaker and a Half	3.59E-10	2.272E-10	1.58
Double Breaker/	4.86E-10	2.271E-10	2.14
Double Bus			
Ring Bus	5.18E-10	4.542E-10	1.14
Single	2.24E-04	2.24E-04	1
Main and Transfer	3.20E-04	2.24E-04	1.43

*J. Bardwell et al. "*Design Guide for Rural Substations*," U.S. Department of Agriculture - Rural Utilities Service, USA, RUS Bulletin 1724E-300, 2001. [Online] Available: https://www.rd.usda.gov/sites/default/files/UEP_Bulletin_1724E-300.

Substation Failure States

Substation Configuration	Failure States
Single	1. Any one circuit breaker fails
	2. Any one control panel fails
	3. The busbar fails
Main and Transfer	1. Any one circuit breaker fails
	2. Any one control panel fails
	3. The main busbar fails (transfer bus only energized in maintenance)
Ring Bus	1. All breakers or their panels fail
	2. Every other busbar fails (non-adjacent)
	 Odd number of inputs (n): (n+1)/n of n busbars fail, two are adjacent
	 Even number of inputs (n): n/2 of n busbars fail
Breaker and a Half	1. Both busbars fail (A and B)
	2. A busbar and one of the opposite input breakers or control panels fail
	 Busbar A and all B input circuits (breakers or panels)
	 Busbar B and all A input circuits (breakers or panels)
	3. All middle circuit breakers fail and one A and one B breaker fails
Double Breaker/Double Bus	1. Both busbars fail
	2. One of the busbars and all the opposite breakers fail
	 Busbar A and all B breakers or panels
	Busbar B and all A breakers or panels



