Electrical Substation Configuration Effect on Substation Reliability

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Abstract: It is crucial that the U.S. electrical grid be reliable, due to its critical role in the economy and our national defense/security. Many common tasks and industrial operations rely on proper electrical power distribution. In designing new bus systems or evaluating existing ones, the type of configuration employed affects the level of risk, reliability, maintenance, and cost involved. The present work utilizes Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) to perform a probabilistic risk assessment (PRA)-based sensitivity study on substation reliability in regard to different bus configurations. This study examines single bus, main and transfer, breaker and a half, double bus/double breaker, and ring bus configurations applied to busses with different numbers of lines. The case variances, methods, and rankings presented herein can help guide bus configurations for electrical grid design/analysis in the future.

1 INTRODUCTION

Utility companies are seeking ways to quantify or numerically analyze reliability, as proven by the amount of growth in power systems modeling and simulation: from $836M in 2017 to billions of dollars by 2022 [1]. Such analysis is essential for ensuring reliable electrical power distribution for other critical infrastructures, or for common simple tasks. The availability of the various substation configuration options explored must also be considered in these analyses. It has long been known that bus configurations can be ranked in terms of reliability; however, quantifying reliability while also considering configuration type and the number of lines affords a more robust basis for cost vs. reliability studies. Traditional probabilistic risk assessments based on the availability of individual components is supported by the Institute of Electrical and Electronics Engineers (IEEE) as a modeling process for designing reliable industrial and commercial power systems [2].

2 BACKGROUND

The U.S. Department of Agriculture's Rural Utilities Service Bulletin 1724E-300, "Design Guide for Rural Substations" [3], outlines six common substation configuration types for application to the electrical power distribution industry: single bus, sectionalized bus, operate/transfer, ring bus, breaker and a half, and double breaker/double bus configurations. This bulletin lists the characteristics, advantages, and disadvantages of each configuration type, and gives single-line diagrams, plan views, and elevation views of a typical bay for each. This information was implemented into the methodology outlined in Section 3.

Although the reliability of these configurations has been studied by other researchers, they did not consider the impact of the number of inputs/circuits. A 2003 study by Tsao and Chang [4] featured a minimal-cut-set-based reliability evaluation of five different types of substation configurations, using the average failure rate, average outage duration, and annual outage time as metrics. But this was only conducted on configurations featuring two lines and two transformers—for a total of four connected circuits. Only a few other papers entail probabilistic studies on various substation configurations, and none addresses inputs as a reliability factor. This knowledge gap is what the present study aims to cover.

3 METHODS

This section details the methods used to calculate and rank the reliability of the most common substation configurations, in consideration of the number of inputs each substation has.

3.1 Scope of Analysis

Five of the six common substation configurations reviewed in the background listed in RUS Bulletin 1724E-300 are considered in this study. The only one not considered is the sectionalized bus, since it introduces additional variability in regard to the location of the section circuit breaker. Varying this additional parameter falls outside the scope of this study. Therefore, only the remaining five substation configurations are considered: single bus, main and transfer, ring bus, breaker and a half, and double breaker/double bus.

This study considers 1–8 lines to inputs per substation. In the IEEE 118 bus test case [5], the median number of lines was four, thus a maximum of double that number was assumed to cover most configurations. In this study, lines are also referred to interchangeably as inputs. Inputs are defined as any circuits connected to the substation which includes lines out to loads, transformers, generators, synchronous conditioners, other substations, or any other type of electrical component.

The failure criteria applied in this study is that a substation is assumed completely failed if it cannot transmit any electrical signal. This does not consider how inputs can disrupt the substation's ability to transmit electrical signals to its other inputs. The components considered in the analysis are circuit breakers, circuit breaker panels, and busbars. Isolation switches are not considered.

3.2 Development of Fault Tree Logic

The fault tree logic was developed based on an understanding of the connections in the configuration. First, a single-line diagram of the bus configuration and its normal operating conditions had to be obtained. Figure 1 contains single-line diagrams (SLDs) adapted from Section 4 of [3].

Second, the failure criteria defined in Section 3.1 must be considered in tandem with the SLD in order to determine the failure states or configuration conditions. These failure states are defined in Table 1. The failure states are explicit combinations of failed components—combinations that fulfill the total substation failure criteria, based on the way they are connected, as shown in the SLD. These failure states encompass the minimal requirement for initiating complete failure of the substation. For example, the single bus configuration only requires that any single component fail for the whole substation to meet the failure criteria. Looking at the SLD in Figure 1a, if a single circuit breaker or its panel fails, this trips the rest of the breakers attached to the busbar and cuts off any transmission through the bus. If the busbar fails, no electricity can be transmitted from one line to another.

Third, the failure states are translated into logic statements in the form of a fault tree. The modeling tool used to set up these fault trees is Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) [6]. These fault tree logics are shown in Figure 2. Each numbered failure state in Table 1 has its own set of component basic events under an individual logic gate. Each logic gate is gathered under an OR gate, representing that any distinct failure state can occur and fulfill the failure criteria. For example, the single bus configuration has three separate branches under the top OR gate: failure of any circuit breaker, failure of any control panel, and failure of the bus. The only failure state not modeled is the third failure state for the breaker and a half configuration since the contribution to the failure rate was a negligible value.

Table 1: Failure states of the considered bus configurations

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

3.3 Fault Tree Calculation

The input data to the SAPHIRE model are from Table 10-4 of [2] and from EPRI 1001873: Appendix B [7]. Basic event names were derived from substations and their inputs in the IEEE 118 bus model [5]. For each model, the logic utilizes substations with a corresponding number of inputs. Across substation configurations featuring the same number of inputs, the same substation and inputs are used. For example, all the logic models with three inputs use the same substation, which has two lines and a load—for a total of three inputs: labeled Bus 7 with Line 6, Line 15, and Load 6. Considering that the failure criterion is no transmission across a substation, the failure data used for the component basic events relate to unavailability per hour. The data used is shown in Table 2.

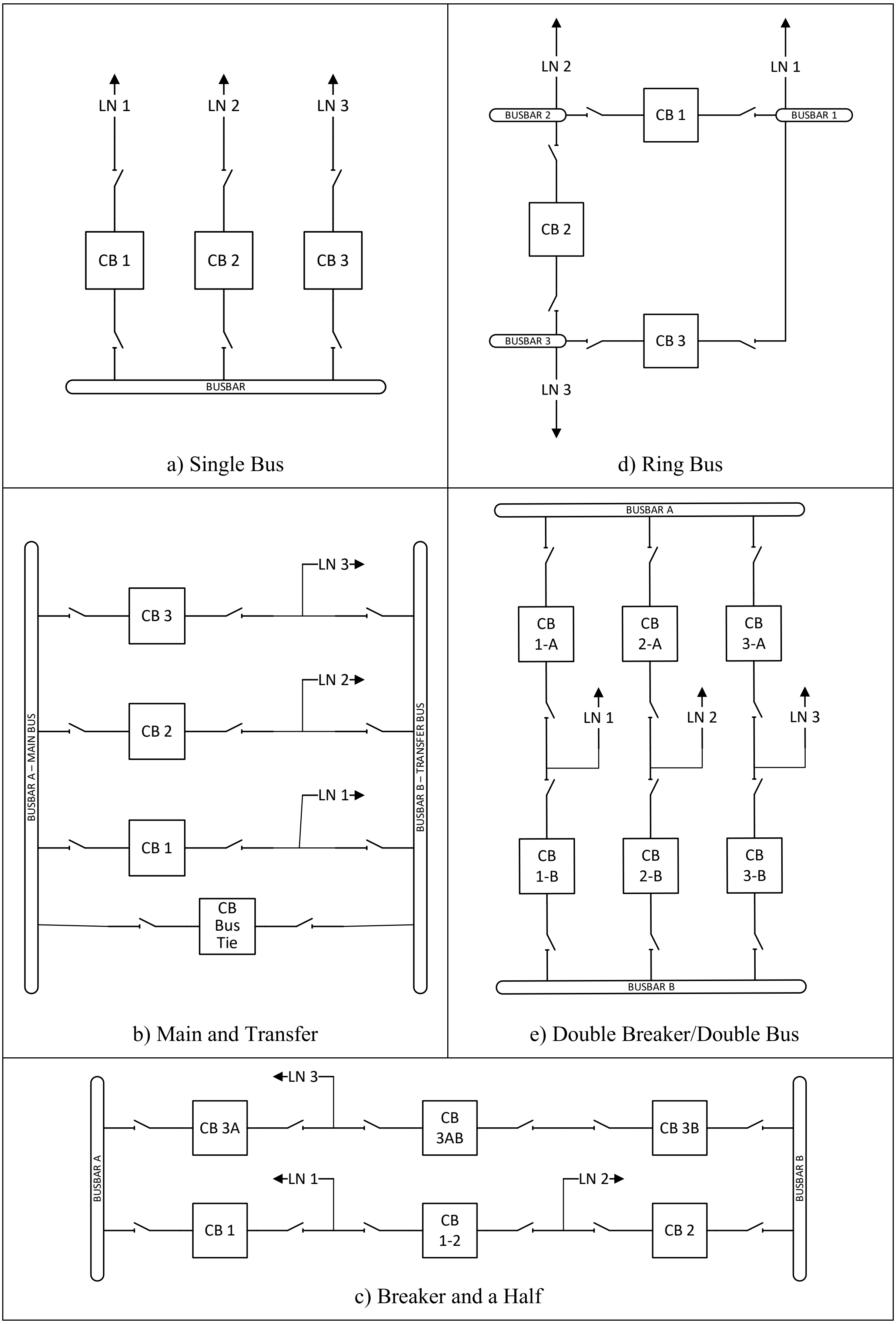
Fault trees were calculated so that the results would reveal all possible minimal cut sets. This was done by setting no truncation value and using the minimal cut set upper bound approximation.

Table 2: Basic event unavailability data

Component	Class	Unavailability [/hr]
> 100 kV Circuit Breaker [7]	Substation Level, Generic	4.931E-05
Busbar, Substation [7]	132 kV Busbars	1.507E-05
Control Panel Switchgear [2]	C4-300	2.845E-06

4 RESULTS

Although a total of 40 fault trees were solved, only 32 are presented here (see Table 3 and Table 4), since the single bus and main and transfer bus logics are presented together as a single result. As seen in Figure 2, the logics were identical and thus so were the results. The results for the ring bus were also identical to those of the single bus with either one or two inputs, because the logic for the ring bus breaks down to the logic of a single bus when using these numbers of inputs. These results were all single-point failures at each component in the substation, thus the number of cut sets simply equaled the number of components in the logic.



a) Single Bus

d) Ring Bus

b) Main and Transfer

e) Double Breaker/Double Bus

c) Breaker and a Half

Figure 1: Single-line diagrams of considered bus configurations with three lines

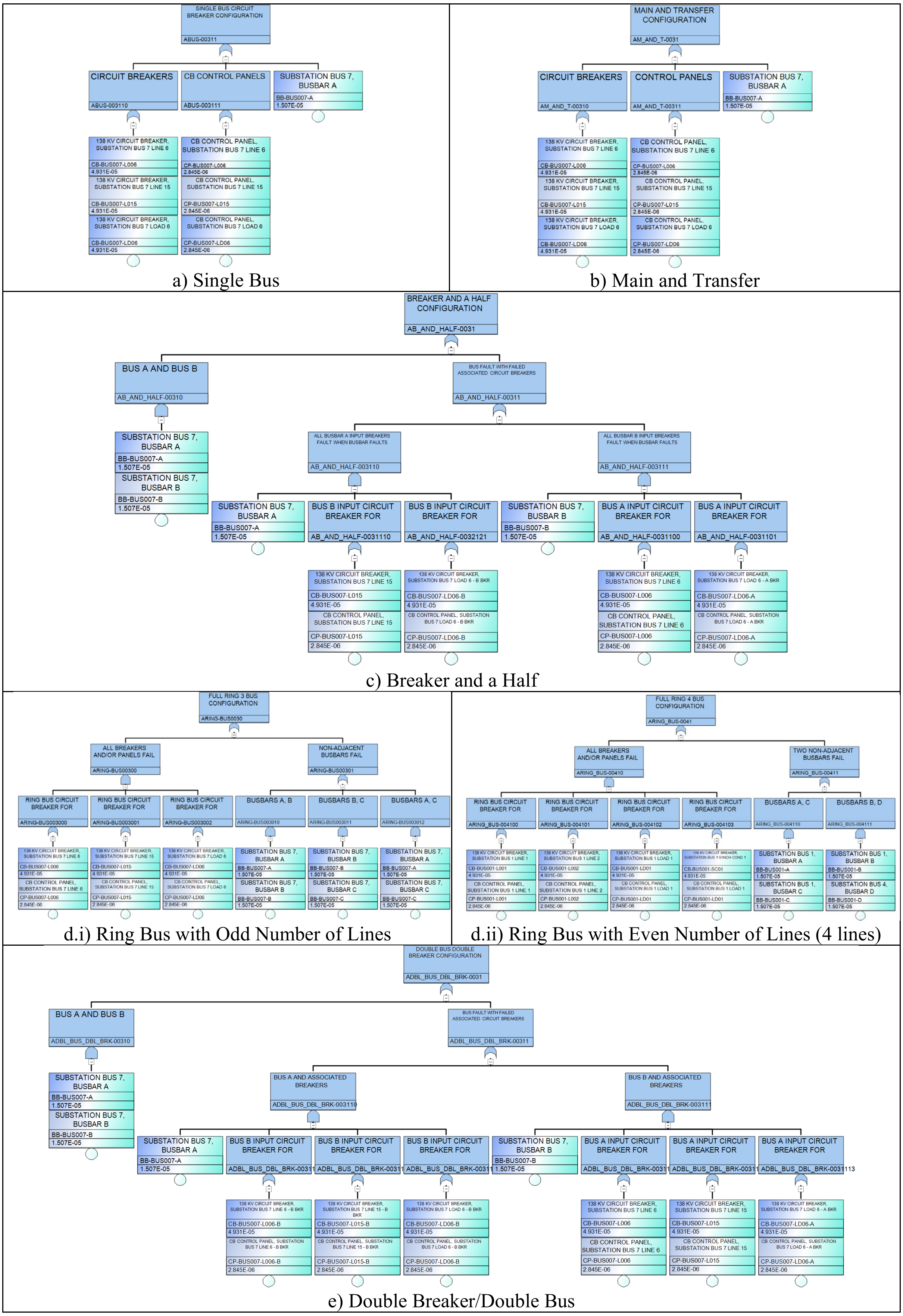


Figure 2: Logic models of considered bus configurations with three lines

Other features of the results are presented below and reference Table 3 to highlight each bus configuration as the number of inputs increase. Results related to data in Table 4 are mentioned later.

- The single or main and transfer configurations are the only configuration types for which the failure rate steadily increased with additional inputs. All other configuration types generally decreased or eventually plateaued, but never increased consistently.
- For the ring bus configuration, the order of magnitude of the failure rate continues to decreases significantly as the number of inputs increases. Most dramatically between two and three inputs with a decrease of 6 orders of magnitude. This is due to the dominance of the busbars which will be discussed further.
- For the breaker and a half configuration, the reliability is identical for every substation with n and n+1 inputs where n is an odd number. For example, for breaker and a half substations with either three or four inputs, the failure rates are identical. This is due to the configuration being identical between the pairs of substations.
- The failure rates for the breaker and a half and double breaker/double bus configurations plateau at about 2.27E-10 at and over three and two inputs, respectively. Beyond those numbers of inputs, the reliability of the configurations is no longer a function of the number of inputs. This is due to the dominance of the busbars which will be discussed further.

Table 3: Failure rate results [/hr]

Bus Configuration \ Number of Inputs	1	2	3	4	5	6	7	8
Single or Main and Transfer	6.7e-05	0.00012	0.00017	0.00022	0.00028	0.00033	0.00038	0.00043
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
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
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

Color scale: 10^{-4}, 10^{-6}, 10^{-8}, 10^{-10}, 10^{-12}, 10^{-14}, 10^{-16}, 10^{-18}

Table 4: Number of cut set results

Bus Configuration \ Number of Inputs	1	2	3	4	5	6	7	8
Single or Main and Transfer	3	5	7	9	11	13	15	17
Ring Bus	3	5	11	10	37	66	135	258
Breaker and a Half	5	5	9	9	17	17	33	33
Double Breaker/Double Bus	5	9	17	33	65	129	257	513

Color scale: 500, 450, 400, 350, 300, 250, 200, 150, 100, 50

Table 5 ranks the configuration types according to failure rate (from least to greatest) and number of inputs. This visualization reveals that, as expected, the single bus and main and transfer bus configurations are the least reliable. Table 3 shows that, for three or more inputs, their failure rate is, at minimum, five orders of magnitude higher than the other configurations.

What is most interesting is that the double breaker/double bus and breaker and a half configuration is most reliable for four inputs or less, but ring buses exceed that by as much as nine orders of magnitude when there are five or more inputs. The maximal difference occurs when there are eight inputs. This can be explained by examining the cut sets. For the ring bus, double breaker/double bus, and breaker and a half configurations, the cut sets that comprise 99% or more of the total failure rate are busbar combinations. The remaining cut sets are composed of circuit breakers and/or breaker control panels. The pairs of busbars for the double breaker/double bus and breaker and a half configurations converge from three inputs because the cut set of the busbar pair dominates. The ring bus continues to rise in reliability by orders of magnitude by the increased number and combinations of busbars. This proves busbars are critical for operating these substations.

Table 5: Ranking of configuration reliability, based on number of inputs

1	2	3	4	5	6	7	8
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
3. RNG	3. RNG	3. RNG	3. RNG	2. BAH	2. BAH	2. BAH	2. BAH
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		

Considering the patterns revealed by looking at the failure rates in Table 3 and Table 5, combined with the results of the number of cut sets in Table 4 and the configurations presented in Figure 1, it can be seen that the configuration and number of components both drive the number of cut sets, but only the configuration drives the failure rate. Comparing the number of cut sets for the ring bus to the number of cut sets for the single or main and transfer and double breaker/double bus configurations reveals that the number of cut sets is driven by the configuration and the number of components. But if you compare the failure rates while considering the number of components, the ring bus's failure rates are multiple orders of magnitude lower than those for the single or main and transfer, and double breaker/double bus configurations, demonstrating that the number of components does not dictate the failure rate.

5 DISCUSSION

The failure rates and cut set analysis, both driven by variability in the number of inputs, provide clearer insight into substation reliability. It was revealed that variability in the failure rates partially corresponds to the number of inputs. In examining the single substation configuration, changing the number of inputs resulted in jumps that were measurable in orders of magnitude. When examining various substation configurations' relative reliability under increasing numbers of inputs, a shift was noted in the most reliable configuration between four and five inputs from the double breaker/double bus and breaker and a half configuration to the ring bus configuration. The analysis also revealed a significant jump in reliability when moving from the single or main and transfer configurations to any of the other three configurations being considered. These nuanced distinctions among the various substation configurations create a foundation for risk-based design and decision making.

Adding cost as a parameter to be considered would build upon this foundational work and further enhance its usefulness for design and analysis. This can be quickly touched upon by using the data published in 2001 in U.S. Department of Agriculture Bulletin 1724E-300 [3] to generate a ranking of substation configurations with four inputs—a ranking that considers both reliability and cost. Table 6 shows that ranking, which is based on multiplying the failure rate by the value given in the approximate relative cost comparison presented in Table 4-1 of the bulletin. The relative cost is calculated in comparison to switching from a single bus configuration, which is why that configuration's approximate relative cost comparison is 1. This quick analysis was only conducted on configurations with four inputs, since those were most readily available. Future work is needed to fully consider all dimensions when determining the overall effectiveness of substation configurations—namely, the influence of the configuration and number of inputs on substation reliability and cost.

Table 6: Ranking of configurations with four inputs, based on reliability and relative cost

Configuration	Multiplied value	Failure rate [/hr]	Approximate relative cost comparison [3]
Breaker and a Half	3.59E-10	2.272E-10	1.58
Double Breaker/Double Bus	4.86E-10	2.271E-10	2.14
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

6 CONCLUSION

This work lays the foundation for a quantified understanding of reliability in relation to two parameters: configuration and number of inputs. To increase the usefulness of these results, more robust costing analyses should be added. This would include current pricing for capital and operation/maintenance expenditures.

Acknowledgements

This work has been supported by the DOE-OE Advanced Grid Research and Development program under AOP #TCF-21-24936.

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