Reliability modelling and analysis for Sheffield Substation 220 kV upgrade project

Sead Pasalic
Caroline Lee
Nicole Eastoe
Transend Networks Pty Ltd
Po Box 606, Moonah, 7009 Tasmania
Australia
Email: sead.pasalic@transend.com.au
caroline.lee@transend.com.au
nicole.eastoe@transend.com.au

Dr Sudhir Agarwal
General Reliability
17194 Russet St., Suite 1,
San Diego, California, USA
Email: sagarwal@gri-us.com

ABSTRACT

This paper describes the application of a defensible probabilistic process in reliability evaluation for Sheffield 220 kV Substation redevelopment project. Sheffield Substation is a hub of 220 kV transmission system in the North and North-West regions of Tasmania. It provides connection to West Coast and Mersey Forth hydro power stations and facilitates power transfers from these power stations to major industrial customers in George Town area and retail and industrial loads in the North and North-West regions of Tasmania. Therefore, it is important that integrity of Sheffield Substation is protected as much as possible and consequences of unplanned outages minimised to prevent possible widespread system disturbances. Together with General Reliability from San Diego, California, Transend undertook the reliability evaluation of four redevelopment options for Sheffield Substation using SUBREL, substation reliability and TRANSREL, transmission system reliability programs.

1. INTRODUCTION

Transend, as a Transmission Service Provider and Transmission Network Operator in Tasmania is responsible for providing reliable electricity supply and providing cost effective development solutions of the transmission network. Transend has identified a need for a comprehensive and more objective process in justification of development projects from its capital works program. The need to combine customer reliability targets and economics to achieve cost effective development solutions has been long recognised. A hierarchical framework for overall power system reliability evaluation is presented in [1]. Different design, planning and operating principles and techniques have been developed in different countries over many decades in an attempt to find balance between reliability targets and economic constraints [2]. Following the reliability concept and principles, different utilities applied different reliability criteria to justify projects from their capital works program. Reliability criteria can be viewed as conditions that should be satisfied by electricity generation, transmission and distribution systems in order to achieve required reliability targets. Reliability criteria usually fall into two categories: established numerical target levels of reliability (eg level of expected energy not supplied) and performance test criteria (eg N-1, N-2 incidents that the system has to withstand). An attempt to combine these two categories into one set of reliability criteria is currently underway in Tasmania [3]. The use of reliability criteria from the first category is the core of probabilistic reliability evaluation approach. The second category is a deterministic reliability evaluation approach. The usefulness of deterministic criteria and security standards in justification of projects from capital works program is challenged in [4]. Instead, an approach involving customers in decision making and simulating a realistic system operation and failure is recommended. The basic steps suggested in proper reliability evaluations are based on complete understanding of the equipment and system behaviour including:

- Understanding the way the equipment and system operate;
- Identify the situations in which equipment can fail;
- Understand consequences of the failures;
- Incorporate these events into the reliability model;
- Use the available evaluation techniques to calculate reliability indices and costs.

With this understanding of the system behaviour probability theory is then only seen as a tool to transform this understanding into the likely system future behaviour.

2. SELECTION OF EVALUATION TECHNIQUE AND SOFTWARE TOOLS

There are two main categories of evaluation techniques [5]: analytical (state enumeration) and Monte Carlo simulation. The advantages and disadvantages of both methods are discussed in [1].Analytical technique was chosen by Transend because of its usefulness in comparing different development options for network development projects. This approach was presented also in the Electricity Supply Association of Australia Guidelines for Reliability Assessment Planning [6]. Consequently, decision was made to acquire SUBREL, and TRANSREL, substation reliability and transmission system reliability programs from General Reliability, USA.

2.1. SUBREL - SUBSTATION RELIABILITY PROGRAM

SUBREL is a computer program which calculates reliability indices for an electricity utility substation and generating station switchyard [7]. The methodology used to analyse impact of substation generated outages on overall system reliability performances has been described in [8].

The program models the following outage events, including all required subsequent automatic and manual switching operations:

1. Forced outage of any substation component:
    - Breaker
    - Transformer
    - Bus Section
    - Disconnector
2. Forced outage of an incoming line.
3. Forced outage overlapping a maintenance outage for substation equipment or an incoming line.
4. Stuck breaker (failure to open when needed to clear the fault).

SUBREL calculates the following load point indices:

- Frequency of Interruption (per year)
- Number of Circuits Interruptions (per year)
- Outage Duration (minutes per outage)
- Annual Total Outage Duration (minutes per year)
- Customer Minutes of Interruption CMI (per year)
- Expected Unsupplied Energy (EUE) (kWh per year)
- Expected Outage Cost ($ per year)

SUBREL also calculates the following substation or total system indices:

- SAIFI, System Average Interruption Frequency Index
- SAIDI, System Average Interruption Duration Index
- CAIDI, Customer Average Interruption Duration Index
- ASAI, Average Service Availability Index
- EUE, Expected Unsupplied Energy (kWh per year)
- Expected Outage Cost ($ per year)

SUBREL generates a list of substation generated outages that can be used further by TRANSREL to analyse impact on overall system reliability performance.

2.2. TRANSREL – TRANSMISSION SYSTEM RELIABILITY PROGRAM

TRANSREL uses contingency enumeration of transmission contingencies to evaluate power network reliability. It is designed to aid electric utility system planners for reliability assessment of bulk power systems. The process involves specifying contingencies (outages of transmission lines and station originated outages) and performing load flow analysis to determine system problems such as circuit overloads, low/high bus voltages, bus separation or islanding. Using the probability, frequency and duration of the contingencies evaluated, indices of system problems as measures of system unreliability are calculated. Both post contingency and post remedial action indices can be calculated. If no remedial actions are taken to alleviate a problem, the post contingency indices may provide a pessimistic assessment of system reliability. If remedial actions such as generation redispatch, switching of facilities, curtailment of load alleviates some of the system problems, the post remedial action reliability indices provide a more realistic measure of system performance. The amount of load shedding is used as an indicator of contingency severity or system capability to withstand contingencies. Using probabilities of contingencies, expected load curtailment at buses can be calculated as reliability indices. TRANSREL was used with load flow program, PTI PSS/E to examine the impact of an outage on system performance.

The types of failures identified for checking the impact of a contingency on system performance are:

Transmission circuit overloads - by comparing flows based on the load flow solution with user selected circuit ratings;
Bus voltage violations - by checking bus voltages against high and low voltage limits, or maximum allowable voltage deviation from the base case;
Load curtailment - by tabulating the amount of load curtailed as a result of system failure;
Load flow divergence - by tabulating the bus mismatches above a predefined tolerance.

TRANSREL computes reliability indices using a contingency enumeration approach, which involves selection and evaluation of contingencies, classification of each contingency according to specified failure criteria, and computation of reliability indices. Reliability indices include frequency, duration and severity (overloads, voltage violations, load curtailed, and energy curtailed). Both system and bus indices are calculated.

3. SUBREL AND TRANSREL APPLICATION FOR SHEFFIELD 220 KV SUBSTATION

Sheffield Substation is a hub of 220 kV transmission system in the North and North-West regions of Tasmania.

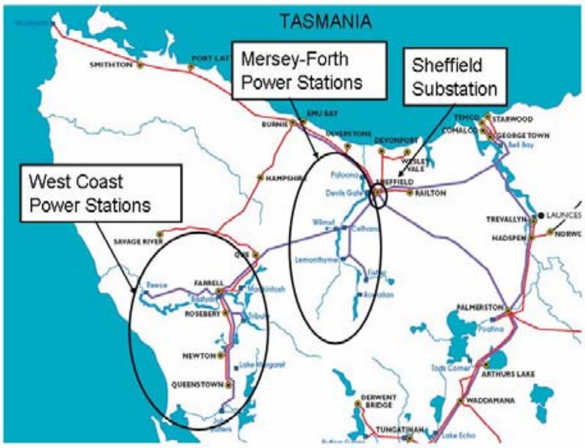


Figure 1: North and North West regions of Tasmania

As shown on Figure 1, it provides connections from the West Coast and Mersey Forth hydro power stations to the rest of the system. In addition, it supplies Aurora Energy customers in North and North-West regions and major industrial customers in the George Town area. During winter months, from May to September, the amount of energy supplied through and transferred from Sheffield Substation can reach more than 50% of the energy supplied to the rest of the system as shown in Figure 2.

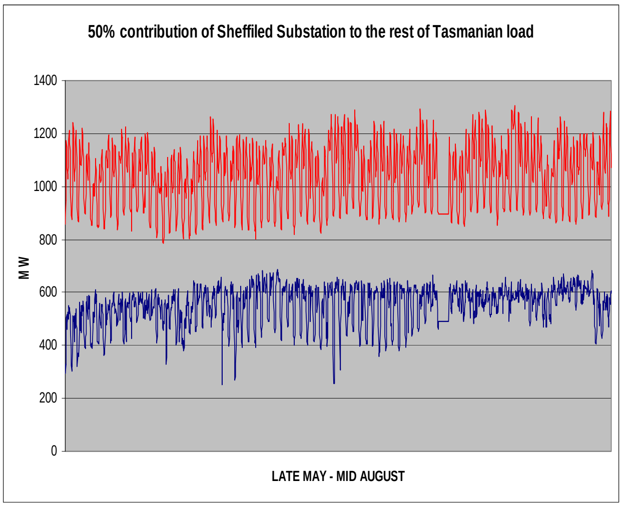


Figure 2: 50% contribution of Sheffield Substation connected generation to Tasmanian load

As such, Sheffield Substation has been recognized as a vulnerable point in the Tasmanian power system. The total loss of Sheffield Substation during times of large power transfer from West Coast of Tasmania to the rest of the system could possibly lead to a large system disturbance in Tasmania. With the present Sheffield Substation 220 kV layout, the total loss of Sheffield Substation can be caused by a single element failure.

3.1. DEVELOPMENT OPTIONS ANALYSED

The need to redesign the existing substation 220 kV layout has been recognised long time ago. The following three options have been selected for detailed modelling and analysis:

Option 1: Triple busbar arrangement

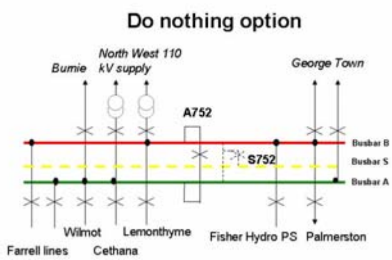
Option 2: Full breaker and a half and double breaker arrangement

Option 3: Partial breaker and half and double breaker arrangement

These options were compared against the existing 220 kV busbar design (Do Nothing option).
A brief description of each of these options is as follows:

3.1.1. DO NOTHING OPTION

The "Do nothing option" represents the existing 220 kV busbar arrangement at Sheffield Substation. The existing 220 kV Sheffield Substation has had some major changes since substation commissioning and installation of two autotransformers for the North and North-West regions of Tasmania supply in 1967. The substation 220 kV busbar arrangement is double, strung busbar arrangement with one bus coupler. In normal system configuration main bus coupler A752 is closed, 220 kV "S" bypass bus and second bus coupler S752 are not in service. The schematic diagram of this option is shown below. Total number of circuits connected at Sheffield Substation is 12. Total number of circuit breakers is 14 (12 plus 2 bus couplers).



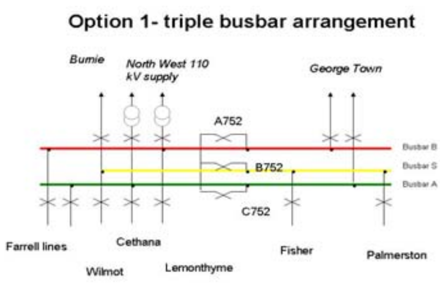
Sheffield Substation is a main supply point to the North-West Region of Tasmania. Total load in the region is around 260 MVA. The fault on bus coupler A752 will result in the loss of both busbar A and B and therefore loss of more than 50% of supply in Tasmania during winter season leading to a blackout in the North-West region. West Coast region will loose synchronism with the rest of the system, experience overfrequency and will be islanded. The rest of the system will experience underfrequency and significant amount of load must be shed to prevent total blackout.

In the case of 220 kV busbar A fault at Sheffield Substation, two elements supplying the North-West region which are the Sheffield–Burnie 220 kV line and autotransformer T1, would be lost. During high winter load the remaining autotransformer T2 will be overloaded and tripped on overload conditions. This will lead to total blackout in the North-West region of Tasmania.

In the case of 220 kV busbar B fault, two elements supplying George Town which are the Sheffield–George Town No 1 transmission line and Sheffield–Palmerston transmission line will be lost. During high winter loads the remaining Sheffield–George Town No 2 line will tripped on overload. This will cause significant change in network impedance with requirement to shed load at major industrial customers at George Town. Consequently, this will produce excessive generation connected at Farrell and Sheffield, which can move the system towards unstable operation and cascade of events with possible blackout in the North and North West regions of Tasmania.

3.1.2. OPTION 1-TRIPLE BUSBAR ARRANGEMENT

The schematic diagram of this option is shown below.

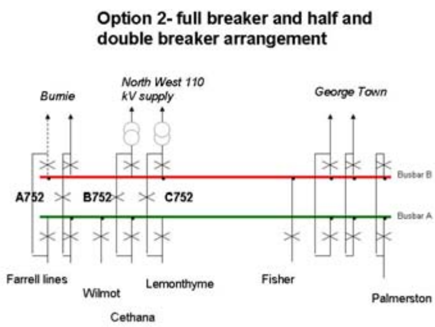


In comparison with "do nothing option" this option proposes to use the spare S752 circuit breaker and upgrade and energise "S" bypass bus to full size. The existing 12 circuits will be spread across the three busbars. Only one additional 220 kV circuit breaker is required in this option.

The total number of circuit breakers in this option is 15.

3.1.3. OPTION 2 - FULL BREAKER AND A HALF AND DOUBLE BREAKER ARRANGEMENT

The schematic diagram of this option is shown below.



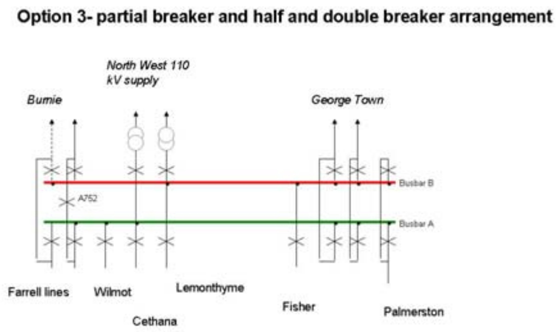
This option includes creating double breaker and breaker and half arrangements. Breaker and a half arrangement is proposed between Hydro Tasmania's Cethana power station and autotransformer T1; and Lemonthyme power station and autotransformer T2.

The total number of circuit breakers in this option is 19.

3.1.4. OPTION 3 - PARTIAL BREAKER AND A HALF AND DOUBLE BREAKER ARRANGEMENT

The schematic diagram of this option is shown below. The main difference in comparison with option 2 is that there is no breaker and half arrangements between Hydro Tasmania's Cethana power station and autotransformer T1; and Lemonthyme power station and autotransformer T2. The establishment of breaker and a half arrangements between these circuits could have as a consequence increase in connection charges for Hydro Tasmania for middle breakers, which needs to be discussed and agreed with this customer.

Total number of circuit breakers in this option is 17.



3.2. RESULTS

In this study, the following outages are examined:

- n-1 forced outage of a station component including transmission lines and transformers
- n-1 maintenance overlapping n-1 forced outages
- breaker stuck condition following a fault. For a fault on line, transformer, bus or a breaker, only those breakers will be considered for being in a stuck condition that are supposed to trip to clear the fault. In this case back up protection will clear the fault.

Apart from the above outages examined, higher order of outages can also be considered and simulated in the programs, however the probability and frequency of their occurrence is quite low. Based on the Transend outage data, it was decided that the above settings should capture most of the credible outage events. The number of events for each of the options is given in the following table. These events are generated by the program to study their impact on substation performance. For each event, the program calculates the probability, frequency and duration. Using the connectivity model, it also computes the amount of loss of load and energy for a load point and for the overall substation. Using a linear flow method it checks if the load can be supplied without violating the ratings of any component.

Options	n-1 Forced Outages	n-1 Forced & n-1 Maintenance Outages	n-1 Forced & n-1 Stuck Outages	Contingencies Considered
Sheffield Existing	28	1300	220	1575
Sheffield Option1	31	1566	186	1813
Sheffield Option2	35	2112	340	2521
Sheffield Option3	32	1740	316	2119

Options	Contingencies Causing Total Load Loss	Contingencies Causing Partial Load Loss	Base Case Probability
Sheffield Existing	0	441	0.9935812
Sheffield Option1	0	130	0.9934282
Sheffield Option2	0	46	0.9931191
Sheffield Option3	0	128	0.9933051

The number of outage events enumerated and examined by the SUBREL program depends on the number of components in a station and the program settings. If more components are added to a station, their exposure to failures also increases. To select an optimal design, a balance between the redundancy provided by adding a component (breaker or a busbar) and the increased exposure should be kept in mind. As seen from the tables above, the number of outage events for options 1, 2 and 3 is higher than for the existing configuration since these options have more breakers and buses in their suggested configurations. There is no event that causes the complete loss of load in the area (including Burnie, Sheffield and George Town substations in the model) in any of the options. However there are events in each option that will cause partial loss of load. Option 2 has the lowest number of events causing loss of load while the existing configuration has the highest number of events causing loss of load.

Reliability indices computed by SUBREL program for each of the option is given in the table below. These indices are computed using the load Probability Density Function (PDF) as unity. PDF of unity means that the load is same throughout the year. The widely used reliability indices such as SAIFI, SAIDI, CAIDI, ASAI, and EUE are computed by the program.

Options	SAIFI	SAIDI	CAIDI	EUE (kWh)	Outage Costs ($)
Existing	0.31222	61.2412	196.14563	249421	4146788
Option1	0.00343	0.76965	224.32008	5930	63661
Option2	0.00473	0.98398	208.16858	9067	642949
Option3	0.03969	7.27084	183.19331	26188	1959675

Outage costs are calculated based on calculated expected unsupplied energy (EUE) and value of lost load applied to particular customer groups. A comprehensive analysis of value of lost load for different customer groups has been undertaken by Monash University for Victorian utilities [9]. Based on the table above it is clear that option 1 – triple busbar arrangement, has lowest outage costs. Based on the list of substation originated outages generated by SUBREL, TRANSREL program was used to indicated consequences on the overall system performances.

The overloads based indices are as follows:

Option	No. of Overloads	Post Contingency Overloads Frequency Based Severity Index	Post Contingency Overloads Probability Based Severity Index
Existing	5	71.37	510.50
Option1	10	144.67	730.04
Option2	15	158.07	770.16
Option3	16	102.54	603.93

The voltage violations were encountered only for option 2 in 9 simulation events. There were few contingencies for which solution did not converge. For these contingencies, a potential exists that the system will face major problems including a collapse. The system stress and its response will, of course, depend on the system conditions present at the time outages. There are four events for Option 1 that result in non-convergence of the power flow. The probability of these non-convergence cases for Option 1 is 0.0026 which means that there is a potential that exists that the system may collapse once every 400 years. This is a very low likely event and during this time the system is likely to go through several changes. It should also be noted that in this analysis no remedial actions are included. With remedial actions, operators may be able to avoid such a situation.

4. CONCLUSIONS

The implementation and application of a probabilistic based planning for selecting a substation configuration provides quite useful information to an engineer in deciding the best option. The use of both SUBREL and TRANSREL programs for Sheffield Substation study has sufficiently demonstrated that it is important to examine all credible outage scenarios that are not possible to do manually. Quantitative indices computed by these programs provide an objective assessment of various options considered. For transmission substations it is important that only SUBREL analysis may not provide the complete information. Without performing a TRANSREL analysis, it is likely that the risk posed by a configuration may not be correctly assessed from the overall system point of view.

For the Sheffield Substation the triple busbar arrangement (Option 1) is the cheapest option, easy to implement, and reliability indices for Sheffield Substation are the best in this option. The low probabilities divergent cases can be resolved with appropriate remedial actions in place, including, generation rescheduling, voltage support and load shedding.

REFERENCES

[1] Billinton, R. and Allan, R.N.,:"Power-system reliability in perspective", IEE Electronic and Power, pp. 231-236, March 1984.

[2] "Power System Reliability Analysis. Application Guide," CIGRE WG 03 of SC 38, Edited by Lesley Kelley-Regnier, 1987.

[3] "Transmission Network Security and Planning Criteria-draft", Office of Tasmanian Energy Regulator, August 2005.

[4] Allan, R.N., and Billinton, R.:"Probabilistic methods applied to electric power systems-are they worth it?",Power Engineering Journal, pp. 121-129, May 1992.

[5] Billinton, R. and Allan, R.N.,:" Reliability Evaluation of Power Systems", Pitmans Books, New York and London, 2nd edition, 1996.

[6] "ESAA Guidelines for Reliability Assessment Planning,", November 1997.

[7] "Subrel-Substation Reliability Program User Manual", General Reliability, San Diego, CA, 2002.

[8] Agarwal, S.K., and Anderson, P.M..: "Effect of Station Originated Outages on Bulk Power System Reliability, ", Cigre Symposium, S 38-91, Montreal, 1991.

[9] Monash University,:*" Study of the Value of Lost Load"* , Study conducted for the Victorian Power Exchange (VPX) company, Melbourne, 2000.