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Reliability Assessment of 60L43 and 60L44

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1. Introduction

60L43 and 60L44 supply three substations designated as RIM, SEA and YYVR from the KI-2 substation source. These three substations are basically double circuit delivery points. The simultaneous outages of the 60L43 and 60L44 can result in complete loss of load at the three substations. 60L43 and 60L44 are basically constructed on different structures except one section that they both are on the common structure about 5 spans. There is a reliability concern from DLoB due to the simultaneous outages of these two lines. This report therefore investigates the reliability of 60L43 and 60L44 and the consequences due to the outages. The reliability benefit/cost analysis is also used in the study to examine whether or not a reinforcement project can be justified, and the maximum investment cost that should be to lead to the project justification using the reliability benefit/cost analysis.

2. Historical Reliability Data

As noted earlier, double circuits, 60L43 and 60L44, supply three substations (RIM, SEA and YVR) from the KI-2 source. As these three substations are double circuit delivery points, the loss of a single circuit will not result in a sustained interruption at the three substations. This section considers the historical actual reliability data of the two circuits and the three substations. These data were obtained from RDMS based on 10 years from January 1996 – December 2005, and they were forced outages (planned outages were not included). The circuit and substation (at delivery point) outages are summarized as follows:

Circuit Outages:

- **60L43**: There are 6 outages during the 10 years (Jan 1996 – Dec 2005). The shortest outage is 1 minute due to lightning, and the longest outage is 19 hrs 53 minutes due to motor vehicle accidence. The rest of the outages (due to foreign object, defective equipment, and adverse weather) are between 58 minutes to 5 hrs 40 minutes. So, unavailability of 60L44 is 2 hrs 55 minutes per year. In other word, availability is 99.97%.
- **60L44**: There are 3 outages during the 10 years. The shortest outage is 1 minute due to foreign object. The longest outage is 19 hrs 45 minutes with unknown cause. Another outage is 9 hrs 21 minutes due to associated equipment. So, unavailability of 60L44 is 3 hrs 8 minutes per year. In other word, availability is 99.96%.

- Note that there is **no simultaneous (double circuit) forced outage for 60L43 and 60L44** during the 10 years. However, there is a forced outage on 60L43 while 60L44 was switched out (maintenance). This event caused all the three substation outages the outage with a duration of 58 minutes for SEA and YVR (supply at RIM was restored earlier).

Substation Outages (at Delivery Point):

- **RIM**: There are 4 outages during the 10 years. The shortest delivery point outage duration is 1 minute associated with switching. The longest delivery point outage duration is 57 minutes due to foreign object.
- **SEA**: There are 2 outages during the 10 years. One outage duration is 1 minute associated with breaker failure, and the other outage duration is 58 minutes due to foreign object.
- **YVR**: There are 4 outages during the 10 years. The shortest outage duration is 1 minute due to lightning. The longest outage duration is 58 minutes due to foreign object

Based on the above outage statistics, SAIDI for this substation group (RIM, SEA and YVR) is **0.013** hrs/yr/delivery point. (Note that our corporate target SAIDI of the entire system is 2.12 hrs/yr/dp). SAIFI (sustained) is 0.025 occurrence/yr/dp. Restoration time (SARI) is 0.541 hrs/occurrence. DPUI (Unserved energy divided by substation group peak load) is 0.10 system-minutes.

Note that the above reliability statistics are based on sustained interruptions (1 minute outage duration and longer). The momentary outages with duration less than 1 minute were practically not included in SAIDI calculation as they were basically due to switching actions (i.e. switched to another circuit when one circuit on outage). For additional information, there are 2 momentary outages during the 10 years; one is at RIM due to defective equipment and the other is at YVR due to foreign object.

3. Reliability Modeling and Results

The simple model for a parallel system can be used to represent the 60L43 and 60L44 as shown in Figure 1.

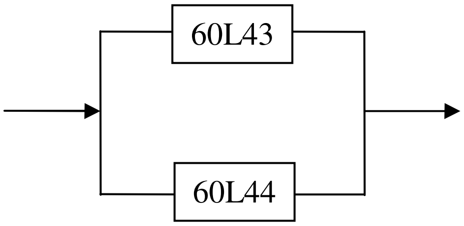

Figure 1: A parallel system representing both 60L43 and 60L44

The forced outage statistics of 60L43 and 60L44 during the past ten years (January 1996 – December 2005) obtained from Reliability Database Management System (RDMS) are shown as follows:

f_{43} : a failure frequency of 60L43 = 0.6 failure/year
f_{44} : a failure frequency of 60L44 = 0.3 failure/year
r_{43} : an average repair time of 60L43 = 5.23 hours
r_{44} : an average repair time of 60L44 = 9.71 hours

Let us assume that the planned outage statistics for both 60L43 and 60L44 are similar, and they are as follows:

f_p : a planned outage frequency = 1 failure/year
r_p : a planned outage duration = 6 hours

The complete loss of load to the three substations (RIM, SEA and YVR) occurs when both 60L43 and 60L44 are on outage at the same time. Therefore, unavailability due to simultaneous (double circuit) outages, excluding planned outages, can be calculated using the following equations.

$f_{system} = [f_{44}(f_{43}\times r_{43}) + f_{43}\times(f_{44}\times r_{44})]/8760 = f_{43}\times f_{44}\times(r_{43} + r_{44})/8760 = 0.0003$ failure/year

$r_{system} = \dfrac{r_{43}\times r_{44}}{r_{43}+r_{44}} = 3.40$ hours

Unavailability (U_{system}) = $f_{system}\times r_{system}$ = 0.00102 hour/year
(Availability = 1 – 0.00102/8760 = 99.999988%)

When including the impact of planned outages (maintenance), the unavailability of this parallel system can be calculated using the following equations.

$f''_{system} = [f_{43}(f_p\times r_p) + f_{44}(f_p\times r_p)]/8760 = 0.0006$ failure/year

$$U''_{system} = \frac{f_{43}(f_p\times r_p)\times\left(\dfrac{r_p\times r_{43}}{r_p+r_{43}}\right) + f_{44}(f_p\times r_p)\times\left(\dfrac{r_p\times r_{44}}{r_p+r_{44}}\right)}{8760} = 0.00191 \text{ hour/year}$$

$r''_{system} = U''_{system}/f''_{system} = 3.18$ hours

The peak load of the three substations (RIM, SEA and YVR) altogether is 138.08 MW and the average load is 89.33 MW based on the load factor of 0.6469. These data were obtained from the PI system during January 2005 – December 2006.

So, Expected Energy Not Supplied (EENS) due to both 60L43 and 60L44 outages is:

$\text{EENS} = U''_{\text{system}} \times (\text{Average Load}) = 0.00191 \times 89.33 = 0.1706$ MWh/year

Delivery Point Unavailability Index (DPUI), which refers to the severity index, is:
$\text{DPUI} = \text{EENS} \times 60 / (\text{Peak Load}) = 0.1706 \times 60 / 138.08 = 0.074$ system·minute

The above DPUI (0.074) is due to the double circuit outages of 60L43 and 60L44 (both forced and planned). The reliability at transmission level should be practically better than when assessing the reliability at the combined transmission and substation level (delivery point). Therefore, the value of 0.074 (transmission outages only) is reasonably aligned with the historical reliability performance of this substation group (DPUI of 0.100 due to transmission and substation outages).

4. Reliability Benefit/Cost Analysis

As results shown in the previous section, the reliability of 60L43 and 60L44 altogether is very exceptional. The outage consequence due to these circuit outages can be expected to have a low impact on socio-economic perspective. This section illustrates the socio-economic impact associated with the double circuit outages of 60L43 and 60L44.

The expected damage cost (EDC) approach can be used as a surrogate of socio-economic costs. The unit interruption cost (UIC) in $/kWh is used in this case to represent the monetary impact on customers due to unserved energy. Customer damage functions obtained from the customer interruption survey [1] are normally used in this approach. The UIC in $/kWh can be derived from the customer damage function as shown in Appendix A [2]. Customer load compositions in the area are also required in order to calculate composite UIC for the specified area. The customer load compositions and the composite UIC for the three substations are in the shown in Table 1. The detailed calculation for composite UIC is shown in Appendix B.

Table 1: Customer load composition and composite unit interruption cost (UIC) for three substations fed by 60L43 and 60L44.

Substation	Customer sector load composition			Composite UIC ($/kWh)
	Residential	Commercial	Industrial	
RIM	57%	39%	4%	15.73
SEA	8%	92%	0%	33.87
YVR	0%	100%	0%	36.70
		Sub-System Average =		**23.86**

Note that the customer load composition at YVR substation is not available. It is assumed in this study that the YVR substation has a purely commercial load, which has the highest monetary impact if the power outage occurs. The expected damage cost (EDC) can be obtained from the multiplication of EENS and the composite UIC.

EDC = EENS×UIC = 0.1706 MWh/yr × 23.86 $/kWh × 1000 = $4070 per year

Note that the EDC value of $4070 per year is considerably at the upper bound of the damage cost estimate as the UIC used in this case is 23.86 $/kWh. If the Gross Demand Product (GDP) is used in damage cost modeling, the UIC based on GDP model is approximately 3.07 $/kWh. The EDC obtained using the GDP based model would therefore considerably lower than $4070 per year.

Reinforcement on 60L43 and 60L44

Assume that the viable reinforcement option to improve reliability of 60L43 and 60L44 is to mitigate the double circuits running on the common structure for about 5 spans. The reliability improvement for this option is therefore directly to the decrement of common mode failures. This option is used in this study for reliability benefit/cost comparison.

Assumptions:

- The failure rate can be decreased by 20% after eliminating the common mode failure of the 5 spans. Therefore, new f_{43} is 0.6×80% = 0.48 f/yr and new f_{44} is 0.3×80% = 0.24 f/yr. It should be noted that the value of 20% of reliability improvement is extremely optimistic as there is no outage record for the common cause failure of these 5 spans during the past 10 years.
- Planned outage statistics remains the same.
- System planning period considered in this study is 20 years.
- Average unavailability remains at the same level during the next 20 years.
- Area load growth is 2% increased rate per year during the next 20 years.
- The total reinforcement project cost is $50k, and an economic life of the reinforcement project is 50 years.
- A discount rate is 6%.

Unavailability of the parallel circuit after the reinforcement is shown below.

$$f''_{\text{system}} = [f_{43(\text{new})}(f_p \times r_p) + f_{44(\text{new})}(f_p \times r_p)]/8760 = 0.0048 \text{ failure/year}$$

$$U''_{\text{system}} = \frac{f_{43(\text{new})}(f_p \times r_p) \times \left(\dfrac{r_p \times r_{43}}{r_p + r_{43}}\right) + f_{44(\text{new})}(f_p \times r_p) \times \left(\dfrac{r_p \times r_{44}}{r_p + r_{44}}\right)}{8760} = 0.00152 \text{ hour/year}$$

$$EENS_{(\text{new})} = U''_{\text{system}} \times (\text{Average Load}) = 0.00152 \times 89.33 = 0.1358 \text{ MWh/year}$$

$$EDC_{(\text{new})} = EENS_{(\text{new})} \times UIC = 0.1358 \text{ MWh/yr} \times 23.86 \text{ \$/kWh} \times 1000 = \$3240 \text{ per year}$$

The reduction in EDC (ΔEDC) after the reinforcement = \$4070 - \$3240 = \$830 per year

The reduction in EDC for 20 years planning period when considering load growth of 2% is shown in Table 2: Note that the reduction in EDC is referred to the monetary benefit gained from the reinforcement.

The annual capital payment (ACP) for this reinforcement project can be calculated using the following equations:

$$\text{Capital return factor (CRF)} = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{0.06(1+0.06)^{50}}{(1+0.06)^{50} - 1} = 0.06344$$

Annual Capital Payment (ACP) = P×CRF = \$50,000×0.06344 = \$3172 per year

Where: P = Total investment cost, i = discount rate, n = an economic life of the project.

The ACP indicates the uniform series of annual payments (an annuity) from the beginning of the construction year through n years for the useful lifetime of the project. This ACP during the system planning period (20 years) is shown in Table 2. Note that the planning period is not necessary to be equal to the economic life of the project.

Table 2: Reduction in the expected damage cost (ΔEDC) and the annual capital payment (ACP) in dollar (\$) per year during the 20 years planning.

Year	ΔEDC (benefit gained)	ACP (cost spent)
1	830	3172
2	847	3172
3	864	3172
4	881	3172
5	898	3172
6	916	3172
7	935	3172
8	953	3172
9	972	3172
10	992	3172
11	1012	3172
12	1032	3172
13	1053	3172
14	1074	3172
15	1095	3172
16	1117	3172
17	1139	3172
18	1162	3172
19	1185	3172
20	1209	3172

The present value (PV) of both costs shown in Table 2 can be calculated using the following equation:

PV of the total ΔEDC = $\sum_{j=1}^{m} \frac{\Delta EDC_j}{(1+0.06)^{j-1}}$ and PV of the total ACP = $\sum_{j=1}^{m} \frac{ACP_j}{(1+0.06)^{j-1}}$

Where: m = planning period.

Therefore, the PV of the total ΔEDC = \$10027

the PV of the total ACP = \$38566

The benefit/cost ratio (BCR) = \$10027/\$38566 = 0.26

The benefit/cost ratio is less than 1.0. This implies that the project cannot be justified based on reliability cost/reliability worth analysis.

In order to be able to justify the project by using benefit/cost analysis driving force. The reinforcement project has to be less than \$15k (i.e. ACP = \$15k×0.06344 = \$952).

This means that although building separate structure cannot be justified based on the benefit/cost analysis, alternative reinforcement option, i.e. building a concrete wall, might be possible only if the investment cost is less than \$15k together with its ability to provide a similar reliability improvement to the case illustrated in this report.

Conclusions

60L43 and 60L44 are considerably reliable. Historical performance SAIDI indicates that a substation group (RIM, SEA and YVR) fed by 60L43 and 60L44 are considerably exceptional (SAIDI = 0.013 hr/yr) compared to the corporate SAIDI of the entire BCH system (2.12 hrs/yr). The study shows that the probability of simultaneous outages of the two circuits is extremely low, and therefore the reliability increment due to system reinforcement is not significant. This is basically due to the system is very reliable. The reliability benefit obtained from the reinforcement cannot justify the investment cost that spends to achieve such a slightly improvement. If the reliability statistics still remain the same as those presented in this report, it is not necessary to conduct system reinforcement at the present time or the near future.

References

[1] R. Billinton, G. Wacker and G. Tollefson, *Assessment of Reliability Worth in Electric Power Systems in Canada*, NSERC Strategic Grant STR0045005, June 1993.

[2] Wenyuan Li, "*Expected Energy Not Served (EENS) Study for Vancouver Island Transmission Reinforcement Project: Part 4 - Effects of Existing HVDC on VI Power Supply Reliability*", British Columbia Transmission Corporation (BCTC), Vancouver, Canada, January 9, 2006.

Appendix A:

A customer interruption cost survey was conducted by the Power System Research Group at the University of Saskatchewan with participation of all major Canadian utilities. This report was released in 1993 [1]. In this survey, a specific customer damage function for BC Hydro system was created and included in the "Capital Planning Guidelines" document of BC Hydro dated April 1, 1993. This customer damage function is shown in Table A1. The customer damage functions shown in Table A1 are expressed in $/kW with different outage durations. The mid value of each duration range is used to convert the $/kW value into the customer damage functions in $/kWh, which is shown in Table A2 [2].

Table A1: Customer damage function for different customer sectors in $/kW.

Duration	Residential	Commercial	Industrial	Unknown mix
0 to 19 min.	0.2	11.4	5.5	1.9
20 to 59 min.	0.6	26.4	8.6	4.0
60 to 119 min.	2.8	40.1	19.6	8.5
120 to 239 min.	5.0	72.6	33.6	15.1
240 to 480 min.	7.2	147.6	52.1	26.5

Table A2: Customer damage function for different customer sectors in $/kWh.

Duration	Residential	Commercial	Industrial	Unknown mix
10 min.	1.2	68.4	33.0	11.4
40 min.	0.9	39.6	12.9	6.0
90 min.	1.9	26.7	13.1	5.7
180 min.	1.7	24.2	11.2	5.0
360 min.	1.2	24.6	8.6	4.4
Average	**1.38**	**36.70**	**15.76**	**6.5**

Appendix B:

The detailed calculation for composite UIC at three substations is shown as follows.

Table B1: Customer load composition and calculated composite unit interruption cost (UIC) for three substations fed by 60L43 and 60L44.

Sub.	Customer composition			Composite UIC (\$/kWh)
	Res.	Comm.	Ind.	
RIM	57%	39%	4%	$0.57\times1.38 + 0.39\times36.70 + 0.04\times15.76 = 15.73$
SEA	8%	92%	0%	$0.08\times1.38 + 0.92\times36.70 + 0.00\times15.76 = 33.87$
YVR	0%	100%	0%	$0.00\times1.38 + 1.00\times36.70 + 0.00\times15.76 = 36.70$

Sub-System Average (Area Average) UIC can be approximately calculated using the composite UIC for individual substations weighted by percentages of their load contributions to the specified area.

Sub-System Average UIC = $15.73\times60\% + 33.87\times9\% + 36.70\times31\%$
= 23.86 (\$/kWh)