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Field Validation of Various Line Rating Methods on a 138 kV Transmission Line in British Columbia

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SUMMARY

Over the years, many techniques have emerged to increase the thermal rating either statically (for static thermal rating, or STR), dynamically (for dynamic thermal rating, or DTR), or quasi-dynamically (for quasi-dynamic rating, or QDTR). This paper is intended to examine various rating methods by using the field monitoring data on a 138 kV transmission line in British Columbia for the period from October 2017 to January 2019. Four rating methods are examined: (a) the BC Hydro standard static rating method (that includes a summer rating and a winter rating); (b) a monthly probabilistic rating method based on local historical air temperature statistics; (c) a quasi-dynamic rating method based on measured ambient air temperature; and (d) a dynamic rating method based on measured conductor temperature. It can be concluded from this case study that: (a) while the current BC Hydro standard rating method has served BC Hydro very well over many years, it could be improved significantly by using the probabilistic rating method. Use of both night-time and day-time ratings may further improve the rating accuracy. (b) The ambient air temperature based QDTR seems to perform reasonably well. This is particularly true for British Columbia where complex terrain and dense vegetation prevails so that wind is highly variable along a transmission line corridor. (c) The DTR result seems to suggest that the 0.61 m/s assumption to serve as a lower bound of actual wind for the rating purpose may not be always valid. Further investigation is required to examine this assumption. (d) A probabilistic load forecast in combination with the probabilistic rating may further enhance the transmission planning, resulting in great cost saving.

KEYWORDS

Ampacity; Conductor; Dynamic thermal rating; Overhead power line; Probabilistic rating; Static thermal rating; Temperature; Transmission line; Weather; Wind.

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INTRODUCTION

Nowadays, one of the biggest challenges facing electric utility companies is how to maximize their existing power line assets' transmission capacity to minimize their investment on building new transmission lines due to the fact that it is very difficult, costly, and time-consuming to procure new transmission line corridors. In many instances, an overhead transmission line's power carrying capacity is limited by its thermal rating. In those instances, it is most cost effective to increase thermal rating without physically modifying a transmission line. On the other hand, NERC requires that "facility ratings used in the reliable planning and operation of the bulk electric system (BES) are determined based on technically sound principles" (NERC 2013). Therefore, it is essential to identify and choose a proper and justifiable rating method for increasing the line rating without compromising the asset and the general public's interests.

There are various rating methods available ranging from traditional deterministic based static thermal rating (STR) methods to modern-day probabilistic based static rating methods, and more advanced quasi-dynamic thermal rating (QDTR) methods, and finally the most advanced full dynamic thermal rating (DTR) methods (Deb 2000; Lu 2014; Cherukupalli et.al. 2010). Every method has its own advantages and disadvantages. Currently, most utilities adopt static rating methods based on either deterministic or probabilistic weather parameters.

This paper is intended to examine various rating methods by using the field monitoring data on a 138 kV transmission line in British Columbia. For this purpose, a quasi-dynamic rating system was implemented in the substation. Moreover, a commercially available dynamic rating system was purchased and installed. Furthermore, weather data at two nearby weather stations was also collected for analysis. The monitoring data covers a period of almost one and half years. These comprehensive data were used to examine the following line rating methods: (a) the BC Hydro standard static rating method (that includes a summer rating and a winter rating); (b) a monthly based probabilistic rating method; (c) the ambient air temperature based quasi-dynamic rating method; and (d) the conductor temperature based dynamic rating method.

Figure 1. Sketch showing the layout of the transmission line from Station B to Station S, and its tap line to Station E, three monitoring sites (Site 1, Site 2, and Site 3) and the two nearby weather stations (D and C). Not to scale.

OVERVIEW OF THE LINE THERMAL RATING MONITORING PROJECT

The thermal rating monitoring project was driven by a local customer's demand for greater capacity than what can be supplied by the BC Hydro standard ratings on a particular BC Hydro owned 138 kV transmission line that is located in the Peace Region of British Columbia. Figure 1 shows the schematic layout of the transmission line from Station B to Station S with a tap line to Station E, the three monitoring sites, and the two nearby weather stations D and C. The transmission line consists of three sections: the BC Hydro owned section shown as solid line with a length of about 15 km, and the two customer owned sections shown as dashed lines with a length of about 6 km (to Station S) and 4 km (to Station E), respectively. ACSR Merlin conductor is used on the BC Hydro owned portion of the line. The line is rated at 90ºC maximum conductor temperature. The project was intended to address the forecasted need of the customer who owns the tap line to Station E. The three monitoring sites were selected accordingly. The weather station D is located approximately 14 km east of Station B, and the weather station C is located approximately 75 km west of Station B. Both weather stations record hourly regular weather parameters, such as ambient air temperature, wind speed and direction, precipitation, etc.

For each monitoring site, one set of commercially available transmission line monitor (TLM) was installed on the conductor to monitor the conductor temperature (among other parameters) at a 10min interval. Thus, there were three TLMs in total. Figure 2 shows the photos for Sites 1 and Site 2, respectively. Site 3 is not shown because the TLM installed at this site malfunctioned. Accordingly, the monitoring data from Site 3 is excluded from this study. This data was used to estimate the line's dynamic rating on a real time basis. The TLMs are self-powered from the conductor's magnetic field. The collected monitoring data is transmitted from the TLMs via a satellite network to a secure cloud server where the raw data is processed, and both the raw data and the rating results are accessible from the website. The TLMs were installed using live-line methods to avoid power interruption to customers.

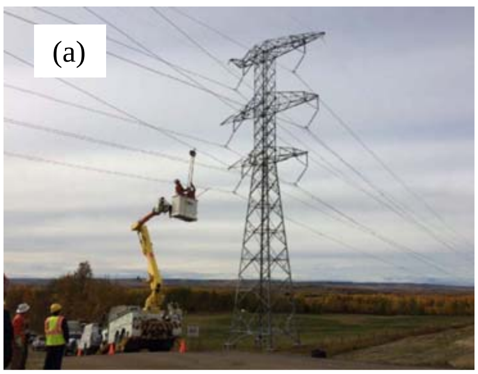

Figure 2. Photos showing (a) Site 1; and (b) Site 2, during the TLM installation.

In addition, a quasi-dynamic thermal rating system (QDTR) was installed at Station B. The system was intended to determine the line's rating (i.e. QDTR) based on the actual ambient air temperature measured at Station B, so that the line can carry greater load than the standard static thermal rating (STR) allows most of time. The system will issue a warning if QDTR is approached, and will trip the line if QDTR is exceeded.

The DTR system was implemented in September 2017, and the QDTR system was implemented in April 2018. They have been in service upto now. All the data collected upto January 2019 were used here for the detailed analysis.

THE BC HYDRO STANDARD RATING METHOD AND ITS RESULT

As a base case, the BC Hydro standard rating method is first presented. As per the current BC Hydro transmission line thermal rating standard, both a summer rating (or ampacity) and a winter rating (or ampacity) are established for every transmission line. Both of the ratings assume a nominal wind speed of 0.61 m/s (2 ft/s) with the wind direction perpendicular to the line. For the summer rating, a nominal ambient air temperature of 30ºC is assumed, and the solar radiation is calculated at 6pm on July 15. For the winter rating, a nominal ambient air temperature of 0ºC or 10ºC is assumed for northern cold regions or southern temperate regions, respectively, and the solar radiation is calculated at 6pm on December 21. The use of 6pm for determining solar radiation is based on the assumption that the peak load would most likely occur around 6pm. In addition, the summer rating is applicable for the months of May to October, and winter rating is applicable for the months of November to April. See Table 1 for the summary of the key parameters assumed in the BC Hydro standard.

Table 1. Key parameters as per BC Hydro standard rating method

Rating	Wind Velocity	Air Temp	Solar Radiation expected on	
			Date	Time
Summer	0.61 m/s	30ºC	July 15	6pm
Winter	0.61 m/s	0ºC / 10ºC *	December 21	6pm

*0ºC for northern cold regions, and 10ºC for southern temperate regions.

This method is essentially deterministic. That is, the key parameters are assumed based on good engineering experience and judgement. It is assumed to be applicable everywhere in British Columbia, regardless of diversity in climates across the province, except for the temperature assumption for the two regions. Therefore, the assumptions may not be always valid. For example, the use of 30ºC for the summer temperature may tend to be conservative for a northern cold region where summer temperature hardly exceeds 30ºC, but may tend to be risky for a southern interior region where summer temperature can often reach 40ºC.

This method is now used to calculate the ratings of the line at the maximum allowable conductor temperature of 90ºC as per the IEEE standard (2012). The result is summarized in Table 2. Also listed in the table is the ratings at noon (12:00) with the same standard assumptions otherwise. Usually, solar radiation is the strongest at noon. Thus, the ratings at noon represent the worst case scenario. It can be seen from Table 2 that the rating at noon is about 14-16A lower than the corresponding rating at 6pm. Therefore, if the peak load occurs before 6pm (perhaps due to a system event), the standard rating result would be overestimated so that it tends to be risky. To address this issue, it is recommended that both a day-time rating and a night-time rating be adopted with use of the rating at 6pm as the night rating to cover the period from 6pm to 6am, and use of the rating at noon as the day rating to cover the period from 6am to 6pm. Therefore, there will be a total of six ratings: the summer night-time rating at 30ºC, the summer day-time rating at 30ºC, the winter night-time rating at 0ºC, the winter day-time rating at 0ºC, the winter night-time rating at 10ºC, and the winter day-time rating at 10ºC.

Table 2. Summary of the BC Hydro standard rating results for the line

Rating Type	Thermal Rating / Ampacity (A)		
	Summer at 30ºC	Winter at 0ºC	Winter at 10ºC
Night-time 18:00 (6pm)	567	716	678
Day-time 12:00 (noon)	553	702	662

THE PROBABILISTIC RATING METHOD AND ITS RESULT

A monthly based, probabilistic rating method is now presented next. Conceptually, a rating can be established on an annual, semi-annual, seasonal, monthly, weekly, or even daily basis. Clearly, an annual or semi-annual rating may be overly simplified due to the great variation of weather over the period. On the other hand, a weekly or daily rating may be overly detailed as two neighbouring weeks or days will not exhibit a significant difference in average weather. Therefore, a monthly based rating is proposed to be a good compromise.

Local historical weather data available from the two nearby weather stations D and C is now used for determining the probabilistic rating on a monthly basis. As wind is greatly affected by local terrain and vegetation so that it is highly variable over both space and time, it is assumed to be 0.61m/s in advance. Solar radiation is calculated assuming a clear sky. Thus, only ambient air temperature is used for statistical analysis. Usually, air temperature does not vary significantly over space, regardless of terrain or vegetation.

First, the daily maximum air temperature data for the last decade (2009-2018) at both weather stations D and C are used to estimate the representative maximum temperature $T_{85\%}$ for every month from January to December by using the following equation

$$T_{85\%} = T_m + 1.036\ T_s \qquad (1)$$

where T_m is the average of the daily maximum air temperature over a particular month. T_s is the standard deviation of the daily maximum air temperature over the month. Thus, $T_{85\%}$ is mathematically the monthly maximum air temperature having 85% confidence level. It is recommended that $T_{85\%}$ be used as the representative maximum air temperature for the given month for the purpose of determining the thermal rating for the month.

Alternatively, $T_{85\%}$ may also be estimated by using the following equation

$$T_{85\%}' = (T_m + T_{max})/2 \quad (2)$$

where T_{max} is the maximum air temperature over the decade of 2009-2018 for the given month.

The statistical data and the results are summarized in Table 3 for D and Table 4 for C. It can be observed from Table 3 and Table 4 that: (a) both Eq. (1) and Eq. (2) produce very comparable result, or $T_{85\%}$ and $T_{85\%}'$ are within about 4ºC; (b) air temperature statistics between the two stations are very comparable even though they are about 90 km apart.

Table 3. Summary of statistical ambient air temperature at the weather station D (2009-2018)

Month	T_m (ºC)	T_s (ºC)	T_{max} (ºC)	$T_{85\%}$ (ºC)	$T_{85\%}'$(ºC)
JAN	-4.74	10.41	11.40	6.05	3.33
FEB	-3.53	8.38	12.60	5.15	4.54
MAR	0.42	7.94	18.40	8.64	9.41
APR	9.25	5.91	29.50	15.37	19.38
MAY	17.27	5.25	29.30	22.71	23.28
JUN	20.66	4.13	31.90	24.94	26.28
JUL	23.15	3.98	33.30	27.28	28.23
AUG	22.39	4.18	31.20	26.72	26.79
SEP	17.22	5.68	31.60	23.11	24.41
OCT	8.90	6.66	23.00	15.80	15.95
NOV	-1.37	8.31	15.40	7.24	7.01
DEC	-6.27	8.85	11.00	2.90	2.37

Table 4. Summary of statistical ambient air temperature at the weather station C (2009-2018)

Month	T_m (ºC)	T_s (ºC)	T_{max} (ºC)	$T_{85\%}$ (ºC)	$T_{85\%}'$ (ºC)
JAN	-3.33	9.55	12.00	6.56	4.33
FEB	-1.27	8.27	13.00	7.30	5.86
MAR	2.06	8.17	20.50	10.53	11.28
APR	10.26	5.84	28.00	16.31	19.13
MAY	17.58	5.42	28.00	23.20	22.79
JUN	20.90	4.30	31.00	25.35	25.95
JUL	23.46	4.32	35.40	27.94	29.43
AUG	22.96	4.33	33.70	27.45	28.33
SEP	17.37	5.91	31.20	23.49	24.29
OCT	9.13	6.39	23.50	15.75	16.32
NOV	-0.72	7.48	15.50	7.03	7.39
DEC	-5.79	8.51	10.40	3.02	2.30

The resulting $T_{85\%}$ values for individual months are now used to calculate the line's monthly rating/ampacity. The results are summarized in Table 5, where $T_{85\%}$(D) or $T_{85\%}$(C) refers to the $T_{85\%}$ value for the weather station D or C, respectively. A_{18}(D) or A_{18}(C) refers to the monthly night-time ampacity (or rating) for the weather station D or C, respectively. A_{12}(D) or A_{12}(C) refers to the monthly day-time ampacity (or rating) for the weather station D or C, respectively. For comparison, the night time and day time summer and winter ratings are also given in the last two rows of Table 5.

The following observations can be made from Table 5:

- As expected, both of the weather stations D and C produce comparable monthly ampacity/rating values.

- The monthly night-time rating is quite significantly higher than the corresponding day-time rating by a value between 12A and 30A depending on the month. Thus, there is a need to distinguish between the night-time and day-time ratings.
- Use of 30ºC for the standard summer rating tends to be conservative at different degrees depending on the month (from May to October).
- This particular line is located in the Peace region which is a northern cold region so that 0ºC would be used for the BC Hydro standard winter rating. Clearly, for this particular line, use of 0ºC for winter rating tends to be risky at various degrees depending on the month (from November to April). On the other hand, use of 10ºC for winter rating tends to be conservative for most of the winter months, except for April.
- Clearly, adoption of monthly probabilistic rating provides a consistent reliability measure across different months, and is far superior over the conventional summer and winter ratings. Use of night-time and day-time ratings further enhance the consistency in terms of reliability measure, resulting in further cost saving.

Table 5. Summary of monthly based, probabilistic ratings for the line using 2009-2018 weather data

Month	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
$T_{85\%}$(D)	22.7	24.9	27.3	26.7	23.1	15.8	7.2	2.9	6.0	5.2	8.6	15.4
$T_{85\%}$(C)	23.2	25.3	27.9	27.4	23.5	15.8	7.0	3.0	6.6	7.3	10.5	16.3
A_{18}(D)	603	590	580	589	620	654	689	705	693	696	683	644
A_{12}(D)	589	578	567	571	590	628	670	691	676	674	655	623
A_{18}(C)	601	588	577	585	618	654	689	705	691	688	676	640
A_{12}(C)	587	576	564	567	589	628	671	690	674	665	648	620
18(6pm)	Summer: 567A at 30ºC						Winter: 678A at 10ºC; 716A at 0ºC					
12(noon)	Summer: 553A at 30ºC						Winter: 662A at 10ºC; 702A at 0ºC					

Note: the rating at 6pm or noon is used to represent night-time (6pm-6am) or day-time (6am-6pm) ratings, respectively.

THE QDTR METHOD AND ITS RESULT

The QDTR is determined using the IEEE method (2012) based on the following key assumptions:

- The ambient air temperature as measured at Station B is representative for the whole line section involved.
- Wind is assumed to be a constant of 0.61m/s with its direction perpendicular to the line.
- Solar radiation is calculated for clear weather at the given date and time as per the solar radiation model described in the IEEE standard (2012).

The QDTR result is summarized in Figure 3 for the period from October 5, 2017 to January 9, 2019, where Day 0 stands for October 5, 2017, and Day 450 refers to December 29, 2018.

The QDTR result can be used to examine the two static methods described earlier. The comparison is shown visually in Figure 3. It can be seen from Figure 3 that:

- The monthly probabilistic ratings A12 (for day-time) and A18 (for night-time) represent the lower bound of QDTR fairly nicely. Thus, the monthly probabilistic rating method as proposed here is well justified.
- The BC Hydro standard summer rating A18(30C) is able to represent, conservatively, the lower bound to the QDTR for the entire "summer" period of May – October for this particular line. On the other hand the BC Hydro standard winter rating A18(0C) cannot be qualified as lower bound to QDTR for a significant portion of the "winter" period of November – April for this particular line. The same is true for the day-time "winter" rating A12(0C).
- According to the original planning forecast, the line maybe overloaded during the summer season of 2018, which is why the thermal monitoring project was launched. However, Figure 3 shows that the actual load was significantly lower than all of the ratings. This is likely the natural result of the deterministic planning method used, in which the worst case load is assumed to occur with certainty. Clearly a probabilistic load forecasting in combination with a

probabilistic rating will significantly improve the utilization of the transmission line with very likely significant cost saving.

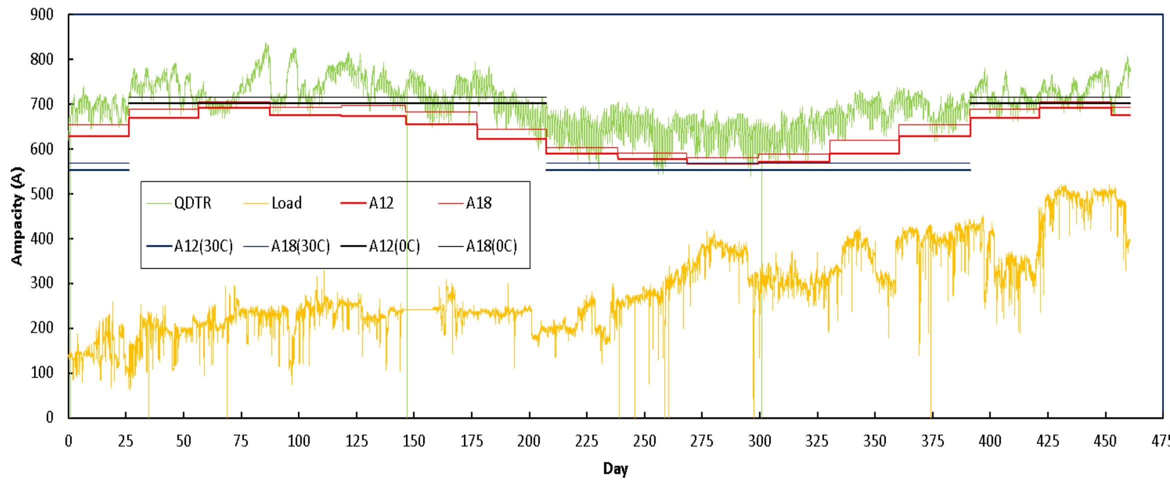

Figure 3. Summary of the QDTR result for the period from October 5, 2017 to January 9, 2019. Also shown for comparison are the load, monthly day-time ampacity A12, monthly night-time ampacity A18, day-time summer ampacity A12(30C) and winter ampacity A12(0C), and night-time summer ampacity A18(30C) and winter ampacity A18(0C).

THE DTR METHOD AND ITS RESULT

The DTR is determined by employing the following method (IEEE 2012):

- Thermal monitors are used to measure conductor temperature, ambient air temperature and electrical load on a real time basis.
- The above three measured parameters are used to back-calculate the effective wind velocity normal to the conductor assuming a clear weather.
- Finally, DTR is calculated based on the measured ambient air temperature and estimated wind velocity assuming clear weather.

The above procedure is repeated for every monitoring instant, resulting in the DTR time series as shown in Figure 4 for monitoring Site 1 and Figure 5 for monitoring Site 2 for the period from October 5, 2017 to January 9, 2019, where Day 0 stands for October 5, 2017, and Day 450 refers to December 29, 2018.

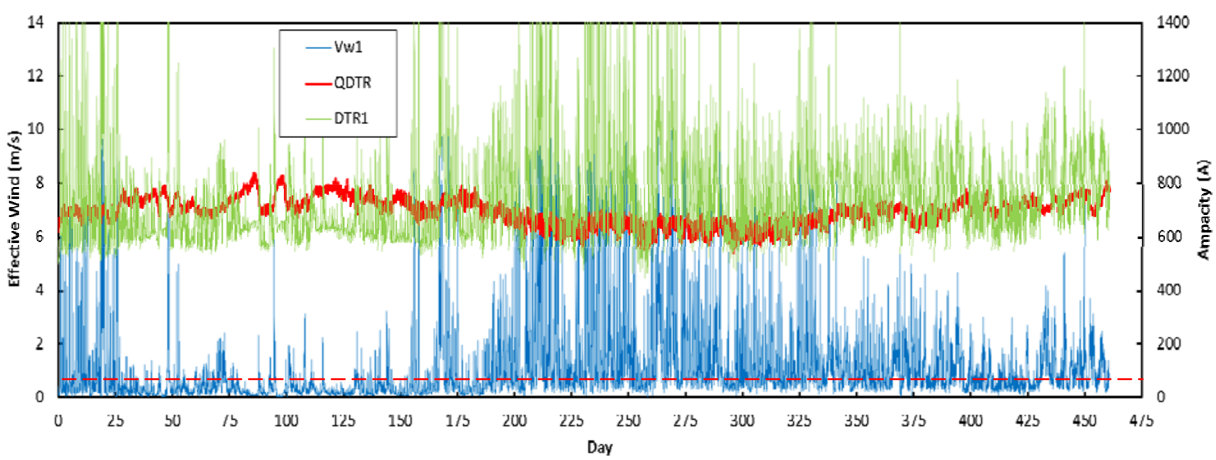

Figure 4. Summary of DTR result for Site 1 (or DTR1). Also shown are the QDTR result and the back-calculated effective wind velocity Vw1. The red dashed line stands for the 0.61m/s wind.

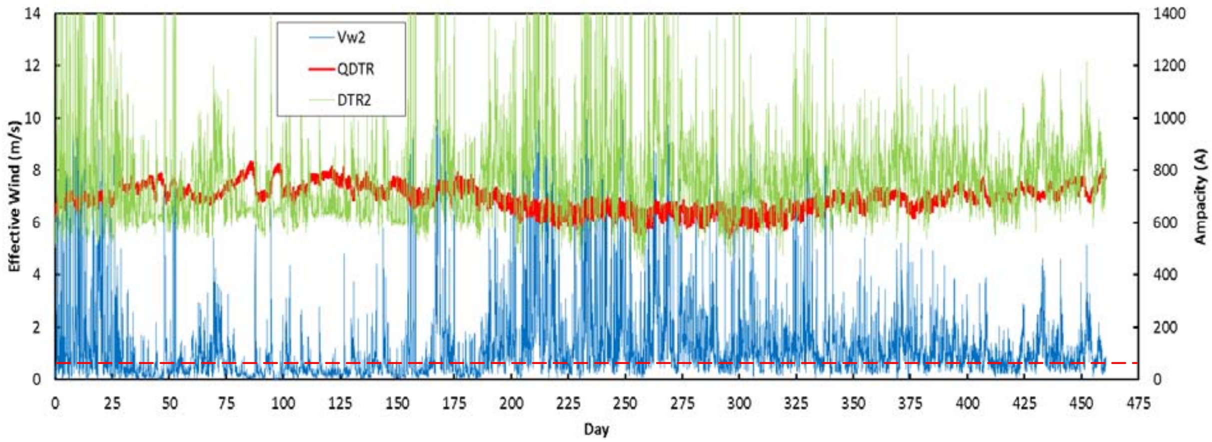

Figure 5. Summary of DTR result for Site 2 (or DTR2). Also shown are the QDTR result and the back-calculated effective wind velocity Vw2. The red dashed line stands for the 0.61m/s wind.

Both Figure 4 and Figure 5 show very similar result and trend: QDTR seems to provide a good lower bound to DTR for the period from about Day 200 to about Day 375. This happens if the effective wind is comparable or greater than 0.61m/s. Otherwise, QDTR cannot be viewed as lower bound to DTR (when the effective wind speed is significantly lower than 0.61m/s). In fact, if the effective wind is exactly 0.61m/s, both DTR and QDTR will take exactly the same value. This comparison seems to suggest that the assumption of 0.61 m/s as a conservative estimate of lower bound wind may not always be valid. This may be particularly true for large portions of British Columbia where vegetation serves as an excellent shield to wind.

CONCLUSION AND RECOMMENDATION

It can be concluded from this case study that:

- While the current BC Hydro standard rating method (which is deterministic based) has served BC Hydro very well over many years, it could be improved significantly by using a monthly based, probabilistic rating method as presented in this paper. Use of both night-time and day-time ratings may further improve the rating accuracy.
- The ambient air temperature based QDTR seems to perform reasonably well. This is particularly true for British Columbia where complex terrain and dense vegetation prevails so that wind is highly variable along a transmission line corridor.
- The DTR result seems to suggest that the 0.61m/s assumption used as a lower bound of actual wind for the rating purpose may not be always valid. Further investigation is required to examine this assumption.
- A probabilistic load forecast in combination with the probabilistic rating may further enhance the utilization of transmission lines, resulting in great cost saving.

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