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The Benefits of using Step-Wise Rating Based on the Trending of Solar Radiation and Ambient Temperature for High Voltage Transmission Line in Malaysia

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Summary

Traditional static line ratings for transmission lines usually take into account the worst case assumptions when determining line capacity rating. In Malaysia, these conservative ratings have been around for approximately 40 years. The values used for ambient temperature, wind speed, solar radiation and other parameters have never been reviewed and thus the same ratings have been used for the past decades. In this regard, it is uncertain if the values assigned to the parameters are still relevant for the present and future application due to the fact that solar radiation values are not static and changes over time. Therefore, the level of certainty in which grid infrastructure is utilised in a highly efficient manner in transmitting power and electrical energy is debatable. This paper looks into the benefits that would be gained, in terms of added capacity and monetary gains by implementing a Step-Wise line rating on Malaysia's overhead transmission line based on the annual trending of actual solar radiation and ambient temperature values. It is found overhead lines that is operated under voltage levels above 132 kV and more bundles configurations shows promising financial benefits.

Keywords

Transmission lines, Ampacity rating, Solar Radiation, Ambient Temperature, Step-Wise

1. Introduction

The transmission line power transfer limit is defined by three main factors which are voltage, stability and thermal limits [1]. While voltage and stability limits are constrained by reliability factor conductor thermal limits are not only governed by reliability factor but also safety factor [1].

Tenaga Nasional Berhad (TNB), the Malaysian power utility company practices Static Line Ratings which takes conservative parameters into considerations when determining a suitable ampacity rating [2]. The practice of static line ratings has been the first and only practice of line ratings in TNB. Static line ratings, limits the amount of current that the conductor is allowed to transmit without breaching safety clearance or accelerate the ageing of conductors [3].

The main factors that determine the static ratings of a conductor are the solar heating, material of conductor, cooling effect of the wind and heat loss from conductor radiation due to temperature difference in ambient temperature and conductor temperature [3]. Due to the rigid characteristics of static line ratings, worst case assumptions were made to acquire conservative parameters to enable these ampacity ratings are valid at all times [3]. While the advantage that it brings is that there is ample buffer of safety margin to avoid any overheating of conductors which will lead to extreme sag that could cause a breach in high voltage clearance, conservative static line rating highly restricts the transmission grid operate at its most optimum capacity.

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Countries with advanced transmission grid technology have shifted to Real-Time Dynamic Line rating to maximize the capacity of their grid infrastructure and avoid overdesign just to prepare for worst case scenario[1]. The working basis of Real-Time Dynamic Line rating largely depends on weather conditions data that is continually monitored [4]. With these weather data, the line rating can be calculated and updated in real-time. This will allow the grid infrastructure to be optimized to a higher carrying capacity while still maintaining the temperature limit of the conductors within safe margin [4].

To implement Real-Time Dynamic Rating on transmission lines will require several weather stations and sensors placed at key strategic locations to obtain reliable real-time data and software to crunch the data to acquire suitable real-time ampacity ratings. This requires a change in current practices.

While the most optimal form is dynamic line rating, a step wise line rating would assist utility companies to alternatively look into finding new ways to better utilise the existing grid infrastructure to meet modern demands. Identifying annual trends in solar radiation could offer a possible step-wise ampacity rating in which benefit could be reaped from the added ampacity ratings during off seasons where solar radiation levels are relatively lower. However, step-wise line rating implementations may not be feasible for all overhead lines as some may not bring the enough benefits to justify the implementation.

Therefore, the objective of this paper is to look into the would-be benefits of implementing a more flexible form of line rating such as the seasonal Step-Wise line rating. The study to this paper will focus on the three high voltage levels in Malaysia which are 132 kV, 275 kV and 500 kV to determine the value of implementing a Step-Wise line rating on each of the different voltage levels.

2. Background

For this study, the voltage levels that will be in the scope are 132kV, 275kV and 500kV. Each voltage level has its own exclusive conductor which will influence the ampacity limit rating along with other factors such as assumed weather conditions.

a. Existing Parameters

The current static line ampacity rating used by the Malaysian power utility company TNB is shown in Table 1 [2]. In Malaysia, there are three main voltage levels of 132 kV, 275 kV and 500 kV for high voltage transmission system. The type of conductors used are mainly Aluminium Conductor Steel Reinforced (ACSR) conductors known to have the equilibrium of both capacity to carry the desired capacity and tensile strength to match the designs of the tower [5].

Voltage (kV)	Type	Bundle	Ampere (A)	MVA/ Circuit
132	ACSR Batang (300mm^2)	1	616	141
275	ACSR Zebra (400mm^2)	2	1433	683
275	ACSR Zebra (400mm^2)	3	2150	1025
500	ACSR Curlew (525mm^2)	4	3233	2800

Table 1 Type and rating of the conductors and Voltage level practiced in Malaysia [2].

Assumptions of weather parameters shown in Table 2 determine the Table 1 ampacity rating. The driver parameters for each ACSR driver are based on the manufacturers published specifications. From the values and parameters acquired in Table 2 and the rating of amplitude in Table 1, it is found that the solar radiation used was set at approximately 1122 $\mathrm{W/m^2}$.

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Parameter Description	Unit	Value
Ambient Temperature	°C	32
Wind Velocity	m/s	0.4469
Elevation	m	50
Absorptivity of conductor surface	-	0.9
Emissivity of conductor surface	-	0.7
Latitude	North	3
Time	24 hrs	12:00
Conductor Temperature Limit	°C	75

Table 2 Parameter values and descriptions currently used for static rating ampacity calculation [2].

b. Annual Trend of Maximum Ambient Temperature

The power utility company in Malaysia, TNB uses the standard of 32°C for static line rating calculation but the most recent data as displayed in Table 3 shows that ambient temperature has increased beyond that.

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Max (°C)	33.0	33.8	33.8	34.7	35.8	34.2	35.5	36.2	35.8	33.9	32.7	32.9

Table 3 Monthly Maximum Ambient Temperature 2018 [9]

The maximum ambient temperature in each month exceeds 32°C and this indicates that the ambient temperature is no longer valid as the conservative rating in Malaysia.

c. Solar Radiation in Malaysia

Malaysia is a tropical country with monsoon season twice in a year that experiences hot and humid weather throughout the year [10]. Malaysia's Latitude Coordinates extend from approximately 1 ° N to 6 ° N and the Longitude extends from 100 ° E to 105 ° E covering both East and West Malaysia [10]. The solar radiation levels are not uniform throughout the year due to the Earth tilt angle and will deviate depending on the Sun's position. Solar radiation (W/m^2) is one of the major determinants of an overhead conductor's amplitude [11][12]. Kota Kinabalu in Sabah and Chuping in Perlis belong to the location with the highest solar radiation in Malaysia as shown in Figure 2 [13]. The solar radiation from Northern Malaysia locations would therefore ideally serve as a reference in determining the line carrying capacity as they are appropriately conservative parameters.

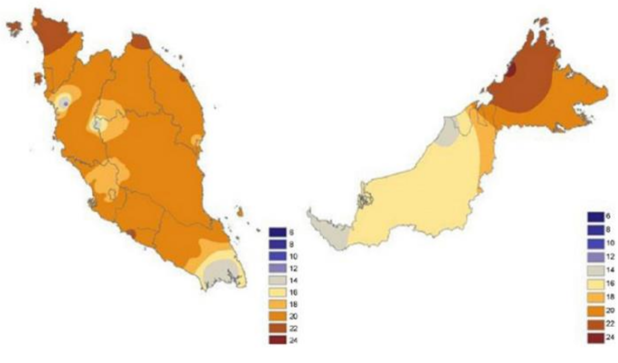

Figure 1 Malaysia average daily solar radiation distribution in terms of *MJ/m*^{2} [13]

i. Annual trend of solar radiation in Kuala Lumpur

A Photovoltaic (PV) solar rooftop case study was conducted in 2016 to 2017 at IKEA Cheras, Kuala Lumpur. This was a manifestation of the initial idea of an annual solar radiation trend. Rooftop PV generation contributes more than 10% of the building's consumption in the months of March, September and October [14], according to the data collected. These months are considered to be months with high solar radiation exposure [14].

ii. Annual trend of solar radiation in Kota Kinabalu

The solar radiation data are recorded daily in Figure 3 and Figure 4 and two values are displayed showing the daily maximum solar radiation and average solar radiation on a daily basis. Daily maximum solar radiation is more relevant for the purposes of this paper and is therefore used in the calculation.

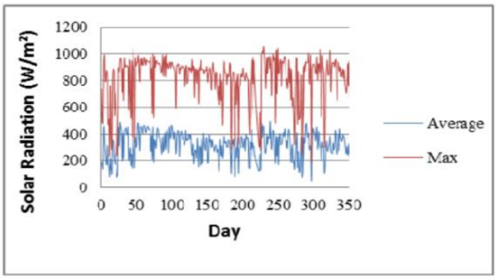

Figure 2 Daily Peak and daily average values of solar radiation in year 2013 in Kota Kinabalu [15].

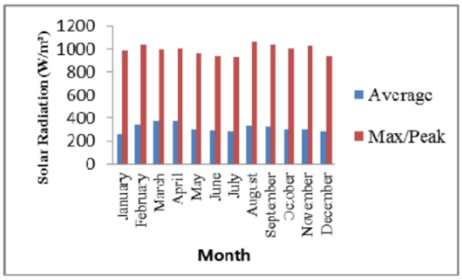

Figure 3 Monthly peak and monthly average solar radiation data in Kota Kinabalu in year 2013 [15].

The highest recorded solar radiation in 2013 was 1056.10 W/m^2, which falls on 18 August [15]. In this analysis, daily data on solar radiation was deemed unclear, instead a monthly solar radiation is used. Figure 4 shows peak solar radiation and average solar radiation, a monthly analysis. With the average monthly data on solar radiation, the annual trend in solar radiation is now clearer. In the months of February-April and August-November, there are two peaks of solar radiation in a year. The months between May and July are experiencing lower solar radiation levels.

d. Step-wise ampacity rating concept

As an alternative to static rating, a slightly more flexible dynamic-like rating is proposed. This rating is decided on the information and data of the trend of solar radiation and ambient temperature. The data on solar radiation show a trend correlating with the Sun's seasons and tilt angle.

Since Malaysia's geographical location is near the equator, the equinoxes is where the highest solar radiation would be experienced while the lowest solstices would be during the summer and winter solstices where the Sun is at the extreme North and South. Every year, the Equinoxes fall approximately on 20 March and 23 September. While Solstices usually fall each year on 21 June and 22 December.

Each season's proposed period is selected depending on the year's solstices and equinoxes. The equinoxes are chosen as the anchors and the days close to the equinoxes are labelled as days with high solar radiation, while the solstices are the opposite. This is the basic structure of how to separate seasonal ampacity. The zones are subsequently calibrated with actual data from 2017 and 2018 to further expand the equinox zone to provide buffer and enhance line reliability.

The implementation of step-wise ampacity could be possible with two-perspective approach. A conservative approach would be to use maximum values of solar radiation and ambient temperatures for the identified periods, while different approach would be to use the median values of solar radiation.

i. Maximum monthly solar radiation data analysis (2017 – 2018)

The first approach to review and update the ampacity line is to replace the existing solar radiation parameter value with the identified maximum recorded solar radiation. The definition of maximum monthly solar radiation in this case is the highest recorded solar radiation in any day of the month. The compiled analysis is shown in Figure 4.

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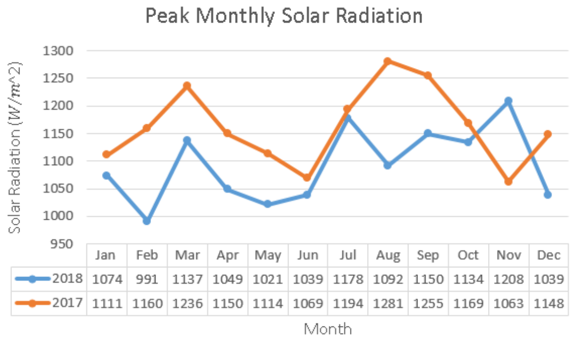

Figure 4 Monthly Peak Solar Radiation year 2017 and 2018 (IPENANGP2 weather station) [9].

In Figure 5, there is a trend in solar radiation. Solar radiation peaks twice a year, in this case March's month is the first peak, while July to October's second peak occurs.

ii. Median monthly solar radiation data analysis (2017 – 2018)

The second approach to reviewing and updating the ampacity line is by replacing the existing solar radiation parameter value with the identified median recorded solar radiation. In this case, the definition of median monthly solar radiation is the mid-value of each of the highest daily recorded solar radiation in each month's day. Figure 6 shows the compiled analysis.

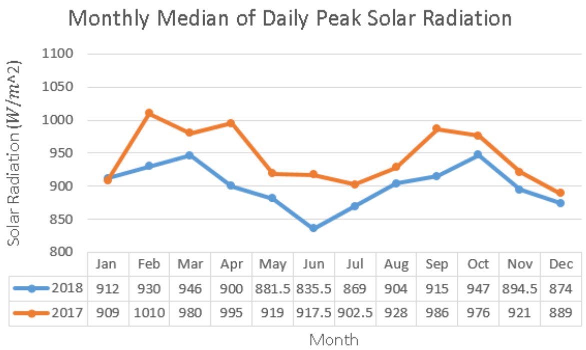

Figure 5 Monthly Median Solar Radiation Analysis 2017 and 2018 (IPENANGP2 weather station) [9].

From the median analysis, the annual solar radiation trend is clear for both years as the peak months receiving abundant solar radiation in the months of March and October. While the June and December months are the two points of relatively low solar radiation levels in a year. The periods from February to April and from September to October showed comparatively higher median solar irradiance compared to other months.

3. Methodology

The value creation of implementing Step-Wise line rating will be measured in terms of power (MVA) and in terms of economic benefit instead of a typical percentage increased in terms of performance perspective. The power comparison will be in terms of MVA per circuit. This will take into account of voltage level and bundles of the conductors.

The main value created by implementing a step-wise line rating is to avoid acquiring land and right of way to erect a new transmission tower or a delay in upgrading of existing overhead lines. In both of these cases, the value gained is not standard and may vary from case to case.

The method used to study the value created from implementing a more flexible line rating will be by looking at how much extra power the existing grid infrastructure can handle by just utilising the assets to a more optimum degree of efficiency.

In Malaysia, the Incentive Based Regulatory (IBR) framework is used to govern the price of tariff charged to consumers and also how the tariff revenue is allocated to each division of the electricity network companies. Figure 6 shows the tariff revenue for each division of the electrical network.

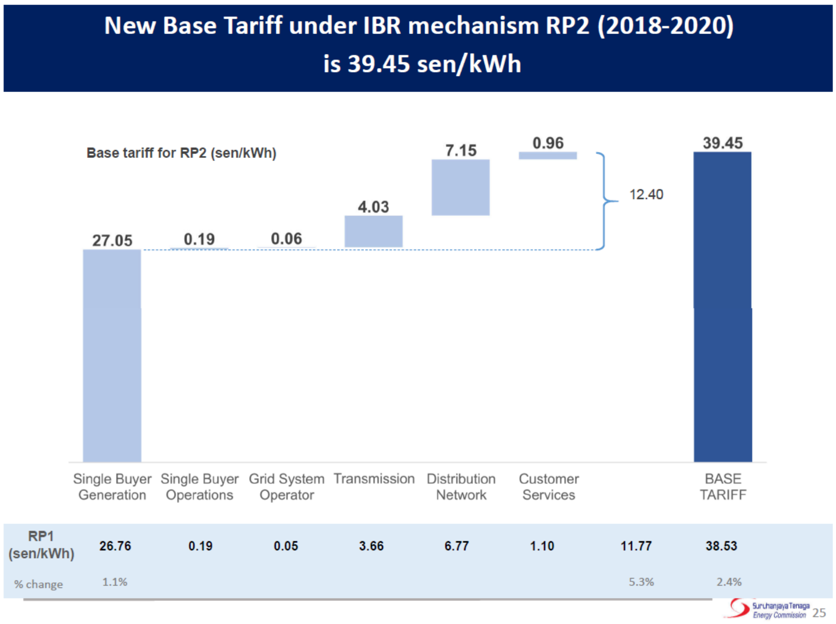

Figure 6 Tariff distribution under the IBR framework for RP2 (2018 – 2020) [16]

High voltage transmission lines falls under the transmission division and each unit of power (kWh) is worth around 4.03 cents and one unit of MWh will worth around 40.3 MYR. This will be the measurement of value creation in terms of financial implications. Financial impact gained is shown in Equation (1).

$$Financial\ Impact\ (MYR\ /\ hour) = 40.3\ (MYR/MVA.hour)\ X\ Difference\ in\ Power\ Transfer\ (MVA)$$

Equation (1)

4. Findings and Results

a. Seasonal Ampacity Limits (conservative approach)

The slightly conservative approach would be employing both the monthly maximum values for solar radiation and maximum ambient temperatures for the consecutive months shown below. Table 4 shows the seasonal step ampacity approach by grouping consecutive annual months which are, respectively, with higher and lower monthly maximum solar radiation values. The chosen periods shown in Table 4 are grouped based on the trending pattern seen in both the peak and median solar radiation graphs in Figures 5 and 6. The identified periods are then assigned with its seasonal ambient temperature based on the maximum ambient temperature apparent for that consecutive months.

Period	1 Mar – 7 Apr	8 Apr – 30 June	1 July – 26 Nov	27 Nov – 28 Feb
Max (W/m^2)	1137	1178	1208	1074
Max Temp (°C)	34.7	35.8	36.2	33.8
ACSR Batang (A)	569	549	538	590
ACSR Zebra (A)	676	651	638	703
ACSR Curlew (A)	761	731	716	792

Table 4 Seasonal Conservative Ampacity limit corresponding to the peak solar radiation and ambient temperature in each period. [17]

b. Seasonal Ampacity Limits (efficiency approach)

The peak solar radiation reading in the day does not last long. Peak solar radiation usually lasts for 20 to 30 minutes before subsiding as shown in Figure 7. Therefore using a highly conservative solar radiation parameter may not be an optimal approach to efficiently utilise the grid infrastructure. If the median solar radiation value used and the line rating is breached during the duration of the solar radiation peak, the excess loading would have been endured for 20 to 30 minutes only.

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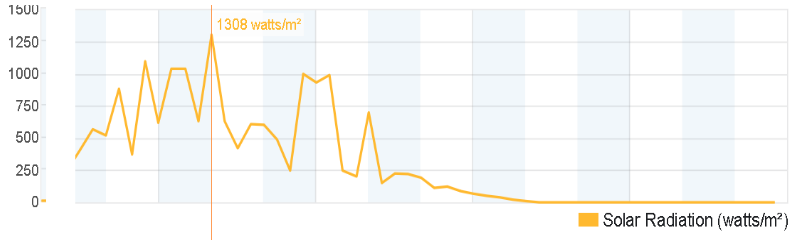

Figure 7 Typical Daily Solar Radiation profile [9].

Therefore, an approach of using monthly median peak solar radiation instead of maximum monthly peak value is done. The efficiency approach ampacity rating is shown in Table 5.

Period	1 Mar – 7 Apr	8 Apr – 30 June	1 July – 26 Nov	27 Nov – 28 Feb
Median (W/m^2)	945	870	902	900
Max Temp (°C)	34.7	35.8	36.2	32.7
ACSR Batang (A)	601	549	592	630
ACSR Zebra (A)	719	721	708	754
ACSR Curlew (A)	812	815	800	853

Table 5 Ampacity rating with Median Solar Radiation Values. [17]

The reason why a median solar radiation value approach is comparably viable than a median ambient temperature approach is the fact that instantaneous incidence and intermittent nature of solar radiation which often results in peak values not sustainable and maintained for long periods of time. Whereas the maximum temperature usually lasts longer as temperature change throughout the days is slower compared to the spikes and dips of solar radiation.

5. Analysis and Impact

The ampacity rating from the findings are translated into power ratings in terms of MVA. By doing so, this will take into account factors that would contribute to the total amount of electrical power transferred such as voltage level and number of conductor bundles. The largest MVA difference is acquired by taking the difference of the high power transfer capacity and the lower power transfer capacity rating. The financial impact gain is calculated by multiplying the MVA difference with the rate of 40.3 MYR/MVA.

a. Seasonal Ampacity Limits (conservative approach)

Table 6 shows the power rating of the Step-Wise conservative approach line rating for voltage levels of 132 kV, 275kV, and 500 kV. The largest differences in MVA and its percentage between the highest and lowest values from the different periods are also tabulated.

Parameter Values	Equinox (Mar)	Solstice (May)	Equinox (Sept)	Solstice (Dec)
Max Solar Rad (W/m^2)	1137	1178	1208	1074
Max Cond Temp (°C)	34.7	35.8	36.2	33.8

Voltage System & Bundle	Equinox (Mar)	Solstice (May)	Equinox (Sept)	Solstice (Dec)	Largest Difference	
					%	MVA
132 kV Single Bundle (MVA)	130	125	123	135	8.9	12
275 kV Double Bundle (MVA)	644	620	608	670	9.3	62
275 kV Triple Bundle (MVA)	967	931	912	1005	9.3	93
500 kV Quad Bundle (MVA)	2638	2535	2481	2746	9.6	265

Table 6 Power Rating of Proposed Step-Wise line ratings (conservative approach)

The largest difference between the seasons is 9.6%. Each voltage level and bundle configuration resulted in a big difference in terms of power transfer capacity added. 132 kV single conductor Batang has only an added capacity of 12 MVA while on the other end the 500 kV quad bundle Curlew has an added capacity of 265 MVA. Financial monetary value correlates to the power transfer capacity added in terms of MVA and not in terms of percentage. All the voltage levels displays similar amount of percentage gain, but this does not mean that each voltage and bundle configuration will reflect in similar financial value creation.

Table 7 shows the financial impact of each of the transmission line configuration of different voltage levels and bundles. Financial gain is defined as the difference in power (MVA) multiplied with the rate of 40.3 MYR/MVA.

Voltage System & Bundle	Largest Difference		Financial impact gained, (MYR/hour)
	%	MVA	
132 kV Single Bundle Batang (MVA)	8.9	12	483
275 kV Double Bundle Zebra (MVA)	9.3	62	2499
275 kV Triple Bundle Zebra (MVA)	9.3	93	3748
500 kV Quad Bundle Curlew (MVA)	9.6	265	10,680

Table 7 Value creation by voltage and bundle configuration in financial terms (conservative approach)

500 kV quad bundle stands to gain the most if operated with Step-Wise line ratings in the seasons where solar radiation and ambient temperature is off peak. The value gained is worth around 10k MYR per hour while optimizing the single bundle 132 kV Batang is only worth around 500 MYR per hour of Step-Wise line rating operation in the off season with the 275 kV Zebra falling in between.

b. Seasonal Ampacity Limits (efficiency approach)

Table 8 shows the power rating of the Step-Wise efficiency approach line rating for voltage levels of 132 kV, 275kV, and 500 kV together with the typical configuration of bundles.

Parameter Values	Equinox (Mar)	Solstice (May)	Equinox (Sept)	Solstice (Dec)
Max Solar Rad (W/m^2)	945	870	902	900
Max Cond Temp (°C)	34.7	35.8	36.2	32.7

Voltage System & Bundle	Equinox (Mar)	Solstice (May)	Equinox (Sept)	Solstice (Dec)	Largest Difference	
					%	MVA
132 kV Single Bundle (MVA)	137	138	135	144	6.2%	9
275 kV Double Bundle (MVA)	685	687	674	718	6.1%	44
275 kV Triple Bundle (MVA)	1028	1030	1012	1078	6.1%	66
500 kV Quad Bundle (MVA)	2814	2823	2773	2956	6.2%	223

Table 8 Power Rating of Proposed Step-Wise ratings (efficiency approach)

The difference between the seasons is around 6.2%. But the 500kV Curlew quad bundle which has an added capacity of 223 MVA while the 132 kV single bundle Batang only added a capacity of 9 MVA while on the other end the 500 kV quad bundle Curlew. Table 9 shows the financial impact of each of the line configuration of different voltage levels and bundles.

Voltage System & Bundle	Largest Difference		Financial impact gained, (MYR/hour)
	%	MVA	
132 kV Single Bundle Batang (MVA)	6.2%	9	363
275 kV Double Bundle Zebra (MVA)	6.1%	44	1773
275 kV Triple Bundle Zebra (MVA)	6.1%	66	2660
500 kV Quad Bundle Curlew (MVA)	7.5%	223	8987

Table 9 Value creation by voltage level and bundle configuration in financial terms (efficient approach)

For the efficiency approach, the difference in power transfer (MVA) is slightly smaller compared to the conservative approach due to the fact that efficiency approach uses median of the daily maximum values of solar radiation which tend to be more uniform while the conservative approach uses maximum recorded solar radiation values which tend to be on extreme ends and will tend to produce a starker difference in results. It is shown that the 132 kV single bundle will benefit the least from a Step-Wise optimized line rating, while the voltage level of 275 kV and 500 kV shows promising financial cases for Step-Wise optimisation.

6. Limitations

The study is only done on a set of weather data location that is meant to cover for the whole of Malaysia due to its high solar radiation and high ambient temperature. In reality, different locations will experience different levels of solar radiation and ambient temperature. There will be similarities in trending of solar radiation and ambient temperature, but there will be differences between the ampacity in the season that limits current carrying capacity and the season that allows for higher current carrying capacity may have a stark difference. Distinctive gaps of high and low ampacity rating will imply a different value creation.

7. Conclusions

It is shown that the 132 kV single bundle Batang does not really bring too much added value after operating the line in Step-Wise instead of the regular Static rating. For voltage levels 275 kV and above, the value created from the added power transfer capacity and financial impact shows promising benefits of operating the transmission line under Step-Wise line ratings.

Circuits with higher voltage levels and more bundles will stand to gain more benefits to implement a Step-Wise line rating that would increase its flexibility and efficiency performance compared to circuits that are configured with a lower voltage level with a lesser conductor bundles. On top of that, the existing infrastructure will be optimised at the higher degree of efficiency without jeopardising the mechanical and electrical integrity of the lines.

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