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#7

Impact of dynamic line rating on operational planning calculations of interconnected transmission systems

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SUMMARY

The ampacity of a conductor presents the maximum constant current that can be carried through the line without violating safety codes, damaging transmission system components and jeopardizing of transmission network reliability. Dynamic Line Rating (DLR) is a technology used to increase the ampacity of electric overhead transmission lines, taking into consideration real operational conditions. Traditionally, ampacity of transmission lines are seasonally estimated assuming unfavorable weather conditions.

However, in the real time operation of transmission system, ampacity of an overhead line increases when wind speed is higher, ambient temperature is lower and solar radiation is smaller than assumed static values. Increase of overhead line ampacity is determined by its ability to dissipate heat produced by Joule effect into the environment, which heavily depends on weather conditions. Because of the conservative assumptions used to calculate static seasonal ampacity limits and the variability of weather parameters, DLRs are usually greater than static seasonal ratings.

This paper describes mathematical model for calculating ampacity of an overhead line, using meteorological data and electrical parameters of overhead line as input. Using historical meteorological data and thermal model, ampacity of critical overhead lines in certain transmission system could be recalculated for every hour of selected test period, with some degree of approximation.

Benefit analysis of DLR method is shown by comparison of N-X security analysis and coordinated cross-border transfer capacity calculation results before and after update of Individual Grid Models (IGMs) with new increased ampacity values. The goal of this paper is to show impact of DLR on network security, frequency of line overloading, network bottlenecks and cross-border transfer capacity.

KEYWORDS

Dynamic Line Rating – Ampacity – Operational planning – Network security – Cross-border transfer capacity

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INTRODUCTION

Thermal current limit (current carrying capacity – ampacity) is defined as the maximum amount of electrical current a conductor or device can carry before sustaining immediate or progressive deterioration [1]. Traditional methodologies for determination of conductor ampacity are mostly based on the static estimation approaches, assuming that operational and weather conditions during the whole exploitation period are closed to the most unfavorable ones. However, ampacity of a conductor is also determined by its thermal constraints, which depends on meteorological conditions in the conductor environment: ambient temperature, wind speed and direction as well as solar radiation.

Dynamic Line Rating (DLR) methods use real time data in order to calculate adequate dynamic ampacity for the overhead lines (OHLs). The aim of DLR is to safely utilize existing transmission lines capacity based on real conditions in which power lines operate [1]. Implementation of DLR methodology should have a positive effect on network in the mean of increasing cross-border transfer capacity, reliability of supply and system security, as well as enabling smooth integration of renewable energy sources.

The purpose of this paper is to present advantages of DLR methodology in comparison to the conventional approaches for determination of thermal current limits. First part of the paper describes theoretical basis and mathematical model used to determine dynamic ampacity of OHLs. In order to estimate impact of DLR methodology on transmission system security and cross-border transfer capacities, two set of calculations are performed on network models: one with ampacity of conductors based on static current approach and one based on DLR methodology. This analysis, presented in second part of the paper, is performed for the most frequently overloaded OHLs and tie lines in the transmission systems of Serbia (RS), Croatia (HR) and Bosnia and Herzegovina (BA).

DLR METHODOLOGIES

In order to save OHLs from thermal deterioration, conductor ampacity is determined based on the maximum conductor temperature or the maximum sag [1]. As the conductor temperature increases (due to increased line current, warmer ambient temperatures, increased solar radiation or decreased wind speeds), conductors elongate and sag, further decreasing the clearance between the conductors and the ground [2]. Conductor-to-ground clearance is one of the design parameters for a transmission line in order to maintain safe distance from vegetation, buildings and other electric power components. So, respecting maximum conductor temperature and the maximum sag during operation of OHLs is necessary in order to comply with operational safety codes.

If we assume that conductor is mechanically properly designed and the sag is not a limiting factor for temperatures below the maximum allowable permanent temperature of the conductor (θ_{cmax}), then the weather conditions have the dominant effect on line's ampacity [1]. In other words, keeping conductor temperature below θ_{cmax} secures safety operation of OHLs. Therefore, monitoring of conductor temperature is crucial for realization of DLR methodology.

Conductor temperature of OHL can be monitored through direct and indirect methods. Direct methods are based on the measurement of the conductor temperature (using temperature sensors, infrared thermal cameras or optical fibers) or at least one physical parameter of the line which is directly related to it, such as line sag, mechanical tension, vibration frequency or line angle of catenary [1]. Indirect methods use weather parameters, measured by meteorological stations, and the conductor electrical load to calculate the temperature of the conductor, through theoretical models [1]. Each of these wide variety of DLR technologies has its own set of advantages and disadvantages.

Determination of conductor ampacity can be based on static or dynamic approach. A crucial difference between static and dynamic line rating is that "static current" is calculated based on rather conventional atmospheric conditions while dynamic line rating takes into account actual atmospheric conditions which most of the time offer better cooling and thus allow higher "dynamic current", contributing to safety improvement [1]. Transmission System Operators (TSOs) mostly use static approach for line rating settings. Static ratings are based on fixed thermal and operating condition assumptions. Typically, these assumptions are based on 98% of the expected worse-case values for key environmental parameters, such as wind speed, ambient temperature, and solar radiation [2]. Furthermore, the assumptions suppose that adverse operating conditions (i.e. low wind, high solar radiation, and high temperature) all occur at the same time. Therefore, real-time dynamic ampacity is often, but not always, higher than its calculated static rating.

Figure 1 describes typical difference between static and dynamic line rating, where it can be seen that for small period of time during the year dynamic current rating (I_{th}) is smaller than static line rating (I_{th_stat}). In this period, TSO would be at risk of exceeding safety margins when operating with maximum ampacity. However, it is observed that increased real-time capacities are available over 83% of the time [2].

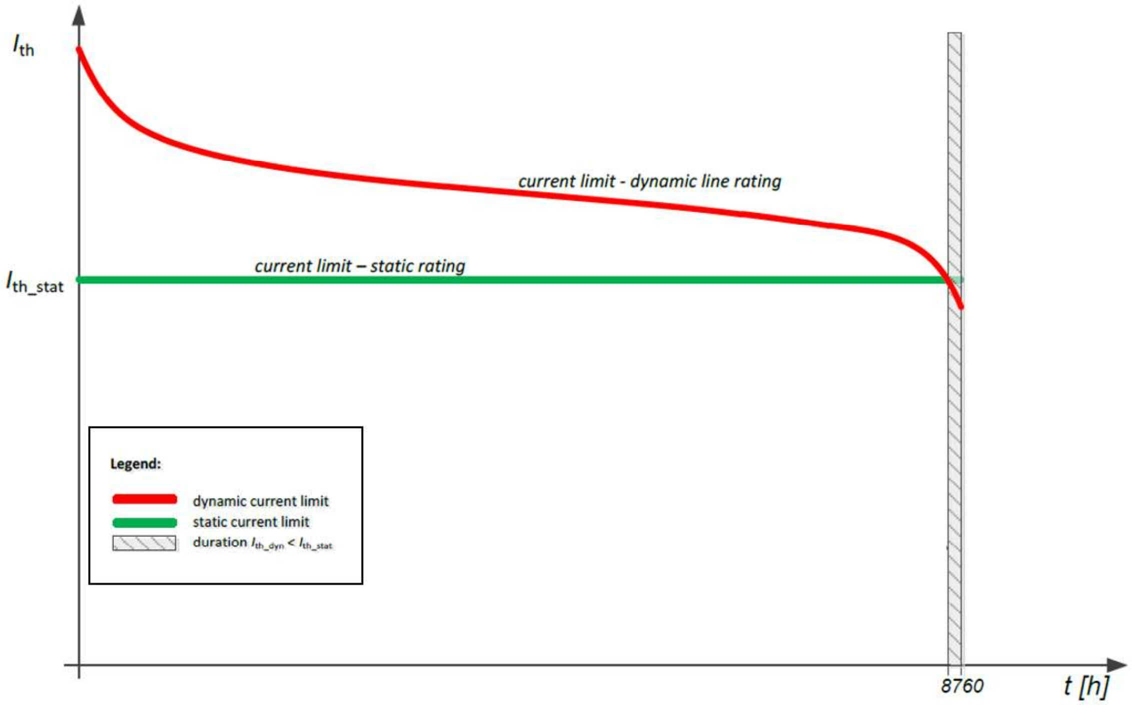

Figure 1. Comparison of static and dynamic current limits [1]

The primary benefits of a DLR implementation include the following [2]:

- Increased transmission system efficiency;
- Decreased capital costs through better exploitation of existing network infrastructures (but it should be emphasized that DLR is not a substitute of grid development);
- Decreased system congestions and improved system security;
- Reduced greenhouse gas emissions through the facilitated integration of renewable energy generation into the transmission system;
- Increased situational awareness and operational flexibility of the transmission system;
- Additional cross-border transfer capacity where it is much needed.

DYNAMIC OHL THERMAL MODEL IN TRANSMISSION SYSTEM OF SERBIA

This paper describes indirect method for DLR calculation, where usage of weather parameters is necessary. Dynamic current rating is calculated from a steady-state heat-balance equation, which balances the thermal energy input and the thermal energy output of the line (i.e. the heat energy that the conductor gains must equal the heat that the conductor gives off to maintain a constant temperature) [2]. The conductor gains heat from the Joule losses and solar radiation. On the other hand, conductor dissipates heat to the surroundings through the processes of radiation and convection. In transmission system of Serbia, steady-state heat-balance equation is based on [3] with some specific approximations:

$$P_J + P_S = P_C + P_R \tag{1}$$

, where variables describe:

$P_J\left[\frac{W}{m}\right]$ – heat gain rate from Joule losses; $P_S\left[\frac{W}{m}\right]$ – heat gain (absorption) rate from solar radiation; $P_C\left[\frac{W}{m}\right]$ – convected heat loss rate per unit length; $P_R\left[\frac{W}{m}\right]$ – radiated heat loss rate per unit length.

Further on, heat gain rate from Joule losses is expressed with equation:

$$P_J = I^2 \cdot R \cdot [1 + \alpha \cdot (\theta_c - 20)] \tag{2}$$

, where variables describe:

I [A] – effective conductor current; $R\left[\frac{\Omega}{m}\right]$ – conductor AC resistance per unit length at temperature 20°C; $\theta_c\,[℃]$ – conductor temperature; $\alpha\left[\frac{1}{℃}\right]$ – temperature coefficient of resistance.

Following (1) and (2), effective current value is given by equation:

$$I = \sqrt{\frac{P_C + P_R - P_S}{R \cdot [1 + \alpha(\theta_c - 20)]}} \tag{3}$$

Heat gain rate from solar radiation is given by:

$$P_S = \alpha_s \cdot d \cdot Q_s \tag{4}$$

, where variables describe:

α_s – coefficient of solar absorption; $d[m]$ – conductor diameter; $Q_s\left[\frac{W}{m^2}\right]$ – intensity of solar radiation.

Heat loss rate per unit length caused by convection is given with the following equation:

$$P_C = \pi \cdot [2.42 \cdot 10^{-2} + 7 \cdot 10^{-5} \cdot (\theta_a + 0.5 \cdot \Delta\theta)] \cdot [0.42 + 0.58 \cdot (\sin\psi)^{0.9}] \cdot 0.57 \cdot \Delta\theta \cdot \left[\frac{v \cdot d}{1.32 \cdot 10^{-5} + 9.6 \cdot 10^{-8} \cdot (\theta_a + 0.5 \cdot \Delta\theta)}\right]^{0.485} . \quad (5)$$

, where variables have the following meanings:

$\theta_a [℃]$ – ambient temperature; $\Delta\theta = \theta_c - \theta_a [℃]$ – difference between conductor temperature and ambient temperature; $\Psi[°]$ – angle between wind speed direction and conductor direction; $v\left[\frac{m}{s}\right]$ – wind speed.

Finally, heat loss rate per unit length caused by radiation is given with equation:

$$P_R = 17.8 \cdot \varepsilon \cdot d \cdot \left[\left(\frac{273 + \theta_a + \Delta\theta}{100}\right)^4 - \left(\frac{273 + \theta_a}{100}\right)^4\right] \quad 6)$$

, where ε presents emissivity coefficient.

By accurately monitoring weather conditions ($Q_s, \alpha_s, \theta_a, \Psi, v, \varepsilon$), knowing electrical parameters of OHLs ($R, \alpha, \theta_{cmax}, d$) and substituting $\theta_c = \theta_{cmax}$, dynamic current rating I_{max} could be determined using equation (3), thereby enabling the system operator to ensure that conductor temperature does not exceed the design limit.

OWERVIEW OF CALCULATION RESULTS

Regional Security Coordinator (RSC) for South East Europe (SEE) region, performs daily N-X contingency analyses for its service users. Merging Day Ahead Congestion Forecast Individual Grid Models (DACF IGMs), that are delivered by TSOs from SEE region, Common Grid Models (CGMs) are created. Then, RSC performs Security Analysis (SA) on created CGMs using contingency and monitoring lists previously predefined by TSO service users.

Based on SA results for Serbian TSO, 82 days of 2017 are identified as critical ones, because overloads of several 400kV and 220kV OHLs were detected. Majority of these overloads occurred during August, September and October, although every month had overload at least for one hour. Additional calculations of Net Transfer Capacity (NTC) values[1] for border between RS and composite of HR and BA (in direction RS→BAHR) are also performed. NTC values are calculated for 3 typical hours (3rd, 11th and 20th) of every critical day. All overloaded OHLs during SA and NTC calculation were included in set of OHLs for witch DLR calculation will be simulated using historical meteorological data (Ω set).

Second part of calculations was committed to determination of dynamic current ratings for all OHLs from set Ω. This process required acquisition of meteorological data for 2017 in geographical areas where these OHLs were located. Due to difficulties in obtaining weather information (this data is not publicly available), several approximations in DLR calculations were imposed:

- Transmission line corridor is described as single span with constant weather conditions along, with strait direction that aligns with majority of real corridor path;
- Lines that are inside 50km radius have same weather conditions.

[1] Calculation of NTC values is done in line with [4].

These approximations enable acquisition of meteorological data only for 6 locations (Belgrade, Niš, Skopje, Sarajevo, Osjek, Mostar) using database from [5]. Also, using single span with linear direction alleviate determination of wind impact, because angle Ψ was easy to obtain.

Using weather conditions, electrical parameters from set Ω and equation (3), dynamic current rating I_{max} were calculated for 17 OHLs for 8760 timestamps for 2017 (hourly resolution). However, based on suggestions in EMS internal technical instruction, current rating of OHLs was defined based on operational admissible current:

$$I_{th} = 0{,}9 \cdot I_{max} \tag{7}$$

Third and final part of calculations was updating IGMs from 82 critical days with current I_{th} as Permanent Admissible Transmission Loading, where static current ratings were previously located. After model correction, all SA and NTC calculations were performed again, this time using dynamic current ratings I_{th}. Results of all calculations are displayed in next sub chapters.

Dynamic current ratings

Table I shows duration of period when dynamic current ratings are smaller than static ones (described in percentages of simulated year), as well as average percentage increase of ampacity for every OHL in Ω set (relative to static current ratings). For the majority of OHLs I_{th} is smaller than I_{th_stat} for less than 7%, indicating that DLR method increase current ratings for more than 93% of time. However, OHL 220kV Feronikl – Prizren 2 and OHL 220kV Bajina Bašta – Vardište stand out with values 14,55% and 11,75%, respectively, indicating that weather conditions could significantly decrease ampacity and potentially create congestion. In these cases, non-steady-state heat balance equation should be used to calculate transient conductor temperature/ampacity in order to determine severity of potential overloads when I_{th} is smaller than I_{th_stat} (which is not scope of this paper).

Table I – Duration of period when I_{th} is smaller than I_{th_stat}, as well as average increase of ampacity for OHLs in Ω set

OHL	Duration when Ith<Ith_stat [%]	Average increase of ampacity [%]
OHL 400kV Pancevo 2 - RP Drmno	0.79	45.16
OHL 400kV Bor 2 - HE Đerdap 1	0	128.47
OHL 400kV Beograd 8 - RP Drmno	0	121.22
TIE 400kV Portile de Fier - Đerdap 1	2.03	41.26
TIE 400kV Mostar - Zakucac	2.76	42.75
OHL 220kV Obrenovac - Beograd 5 (250)	5.4	37.6
OHL 220kV Obrenovac - Beograd 5 (294A)	5.4	37.6
OHL 220kV Obrenovac - Beograd 5 (228)	5.4	37.6
OHL 220kV Srbobran 2 - Sremska Mitrovica 2	0.14	76.39
TIE 220kV Prizren 2 - Fierza	1.3	53.44
OHL 220kV Obrenovac - Valjevo 3	2.76	44.82
OHL 220kV Feronikl - Prizren 2	14.55	22.34
OHL 220kV Obrenovac - Beograd 3	2.74	41.57
OHL 220kV Obrenovac - Bajina Bašta	6	32.27
OHL 220kV Bajina Bašta - Vardište	11.75	27.27
OHL 220kV Pancevo 2 - NIS	6.36	38.9
TIE 220kV Vardište - Višegrad	0.54	43.55

Analyzing column *Average increase of ampacity* from Table I led to the conclusion that OHL 400kV Bor 2 – HE Đerdap 1 and OHL 400kV Beograd 8 – RP Drmno could be (on average) loaded twice as much it's static current ratings. Rest OHLs have average increase of ampacity in range 22÷76 [%], gravitating to the most common 40% value.

Figures 2, 3 and 4 describe relationship between dynamic and seasonal (static) ampacity time series for 3 typical OHLs. Similar curves could be obtained for rest OHLs from Ω set. Common conclusion for all OHLs is that hours when I_{th} is smaller than I_{th_stat} dominantly occur during winter season.

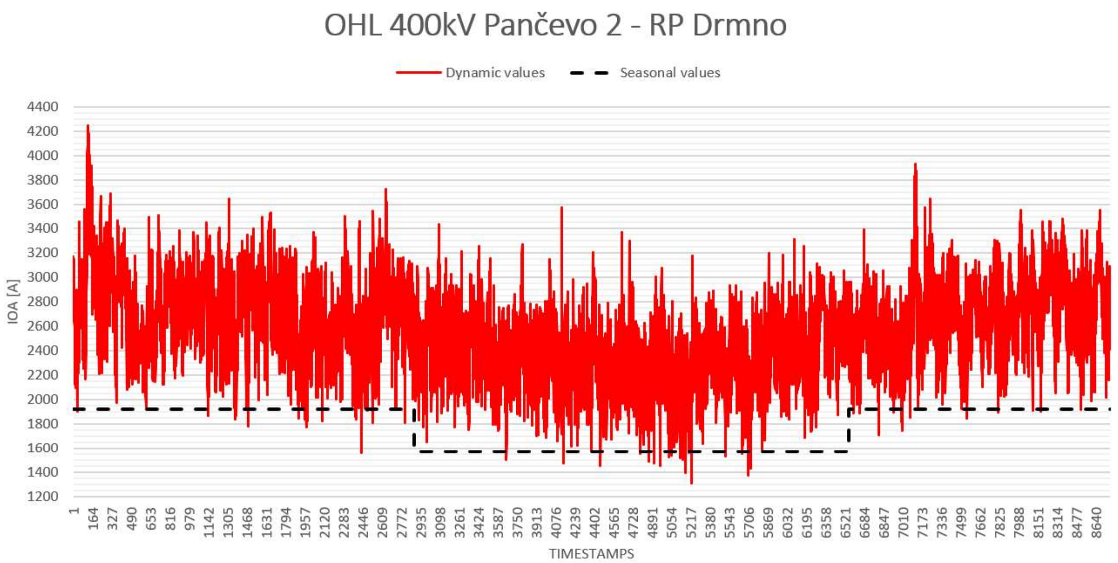

Figure 2. Comparison of dynamic and seasonal ampacity for the most overloaded 400kV OHL in original SA

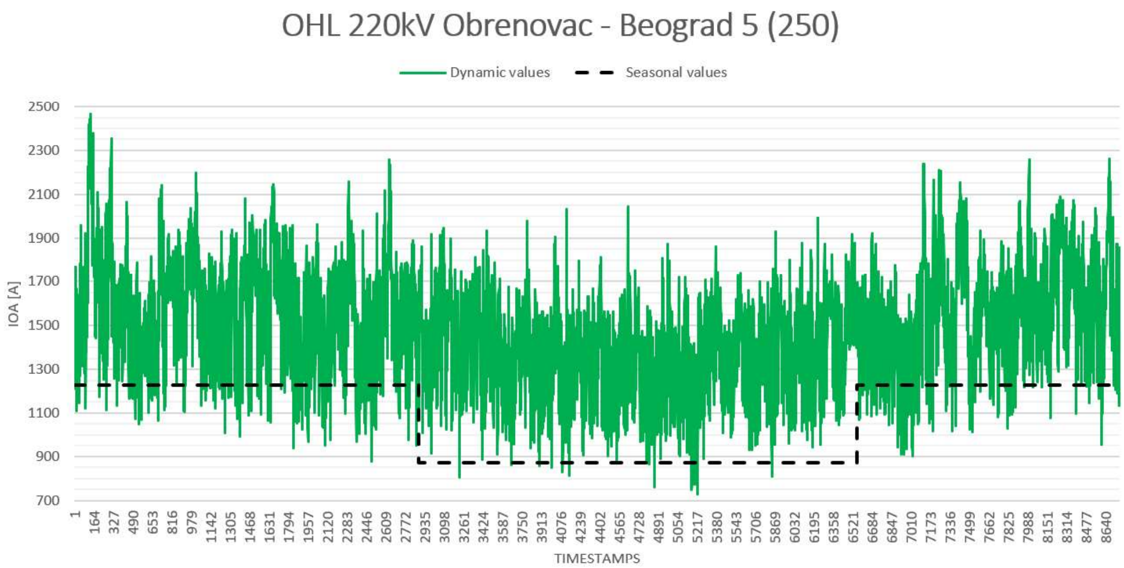

Figure 3. Comparison of dynamic and seasonal ampacity for the most overloaded 220kV OHL in original SA

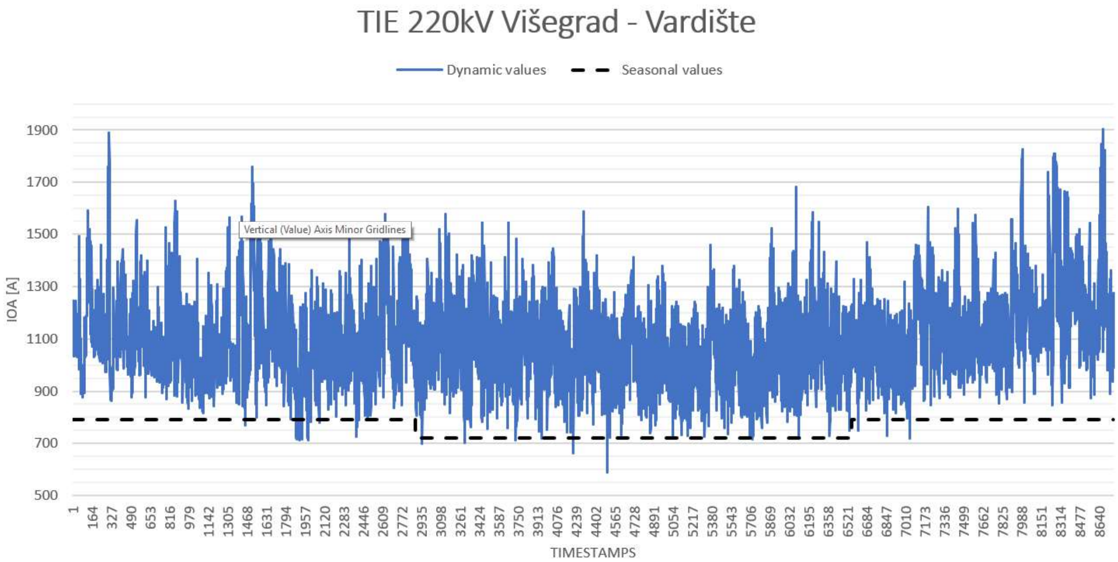

Figure 4. Comparison of dynamic and seasonal ampacity for the most overloaded OHL in original NTC calculations

Further investigation of this occurrence revealed that I_{th} values are dominantly influenced by P_C component of heat. Dominant factor in equation (5) is product component $\Delta\theta$, which means that P_C is heavily influenced by temperature difference between conductor and ambient and not by wind speed, as it is expected. Very warm springs and autumns lead to situation where $\Delta\theta$ value is smaller in real conditions than constant $\Delta\theta$ value calculated for seasonal approach – meaning that I_{th} are smaller than I_{th_stat}.

Security analysis

Table II displays SA results calculated with seasonal and dynamic current ratings. By comparing two sets of SA calculation results it is obvious that number of overloads, as well as maximum value of overload (both of them per OHL) decrease after applying dynamic ampacity values onto the IGMs. Several overloads even disappeared after using DLR approach. This analysis proves that DLR method could increase overall system security and reduce potential congestions if it is implemented on multiple OHLs located on wider network area.

Table II – Overview of overloads occurred during SA performed on two sets of IGMs

	Calculation with seasonal ratings (Ith_stat)			Calculation with dynamic ratings (Ith)		
Overload Name	Minimum loading[%]	Maximum loading[%]	Number of repeating	Minimum loading[%]	Maximum loading[%]	Number of repeating
OHL 220kV Obrenovac - Beograd 5 (250)	90.00628	170.001419	570	90.00628	146.8487	272
OHL 220kV Obrenovac - Beograd 5 (294A)	90.00518	137.115662	485	90.04444	102.124413	7
OHL 400kV Pančevo 2 - RP Drmno	90.0067749	111.6051	262	90.25613	114.144493	13
OHL 220kV Obrenovac - Beograd 5 (228)	90.9224548	155.919922	207	90.04365	136.2353	36
TIE 220kV Prizren 2 - Fierza (RS)	90.01116	147.965439	130	91.06119	131.5057	33
TIE 220kV Prizren 2 - Fierza (AL)	90.0422745	147.473038	121	90.5757141	131.021545	33
OHL 400kV Bor 2 - HE Đerdap 1	90.0176239	102.249336	77	-	-	0
OHL 220kV Obrenovac - Valjevo 3	90.01093	104.733955	60	-	-	0
OHL 220kV Feronikl - Prizren 2	90.13319	113.644295	40	90.48078	96.55325	3
OHL 220kV Obrenovac - Beograd 3	90.0852	110.6874	20	94.47676	94.47676	1
OHL 400kV Beograd 8 - RP Drmno	90.06181	94.98565	14	-	-	0
TIE 400kV Vardište - Višegrad (BA)	90.3192749	90.62821	4	-	-	0
OHL 220kV Obrenovac - Bajina Bašta	90.20549	90.94789	3	-	-	0
TIE 400kV Portile de Fier - Đerdap 1 (RO)	90.38842	91.44813	2	90.5855942	90.5855942	1
OHL 220kV RHE Bajina Bašta - Bajina Bašta (292B)	117.1735	117.1735	1	-	-	0
OHL 220kV Pančevo 2 - NIS	90.69053	90.69053	1	-	-	0

NTC calculation

Figures 5 and 6 display percentage shares of specific OHL among all OHLs which overload stopped capacity calculation process and determined NTC value in two separate cases, one with seasonal ratings and one with dynamic ones. The most occurring overload TIE 220kV Višegrad – Vardište in case of seasonal ratings, is about 5 time less present after using dynamic ampacities. Also, these pie charts reveal that two most overloaded OHLs in both cases, with summary number of occurrences more than 80% are connected with TS Vardište, meaning that this part of the network should be developed by adding some new tie lines.

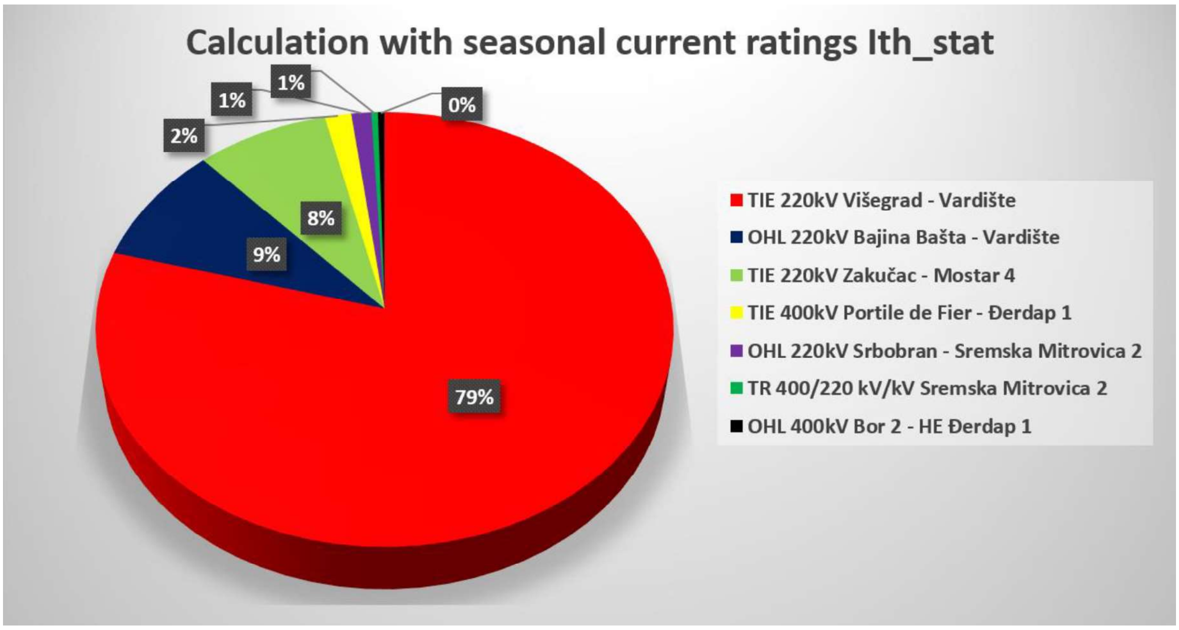

Figure 5. Percentage contribution of specific OHL overload in case of using I_{th_stat}

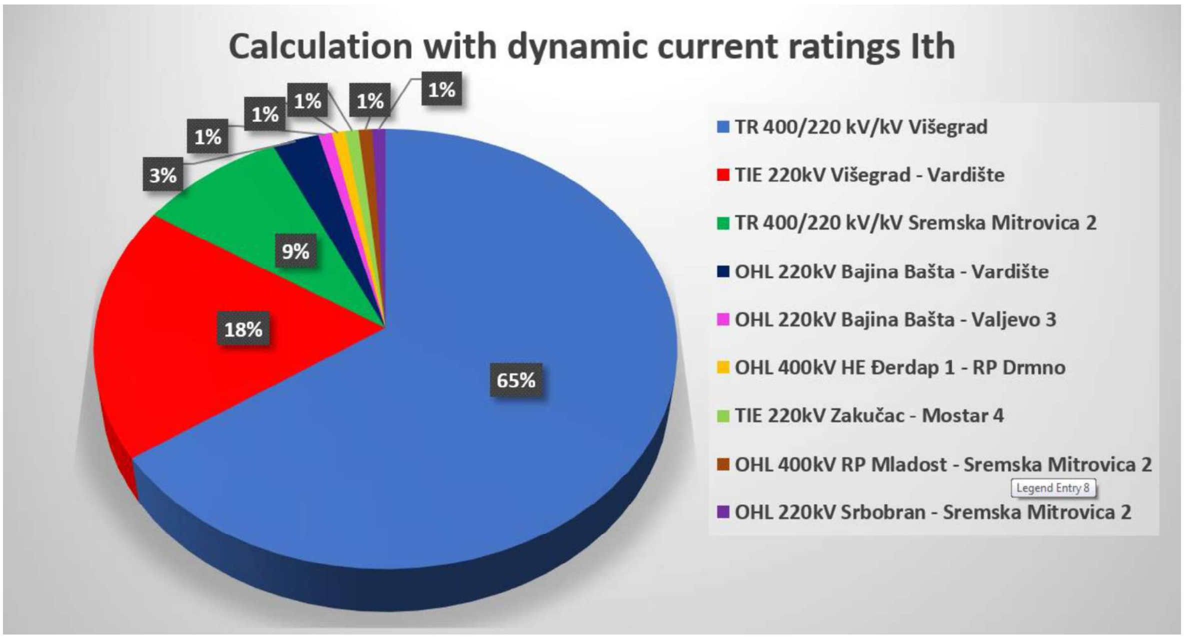

Figure 6. Percentage contribution of specific OHL overload in case of using I_{th}

Figure 7 displays differences between NTC values calculated before and after update of dynamic ampacity values into IGMs. Different bar colors describe different hours of 82 critical days. It can be seen that on average NTC values increase for about 300MW on border RS→BAHR. For small number of hours (usually for 11th hour), NTC is actually smaller than one calculated with seasonal ratings, which is a consequence of unexpectedly higher real ambient temperatures than predefined seasonal ones (in our case predefined seasonal temperatures are 15 ℃ for winter and 35 ℃ for summer). By comparing this delta NTC values with NTC values obtained with I_{th_stat}, average increase of NTC values is around 35%, which is more than significant.

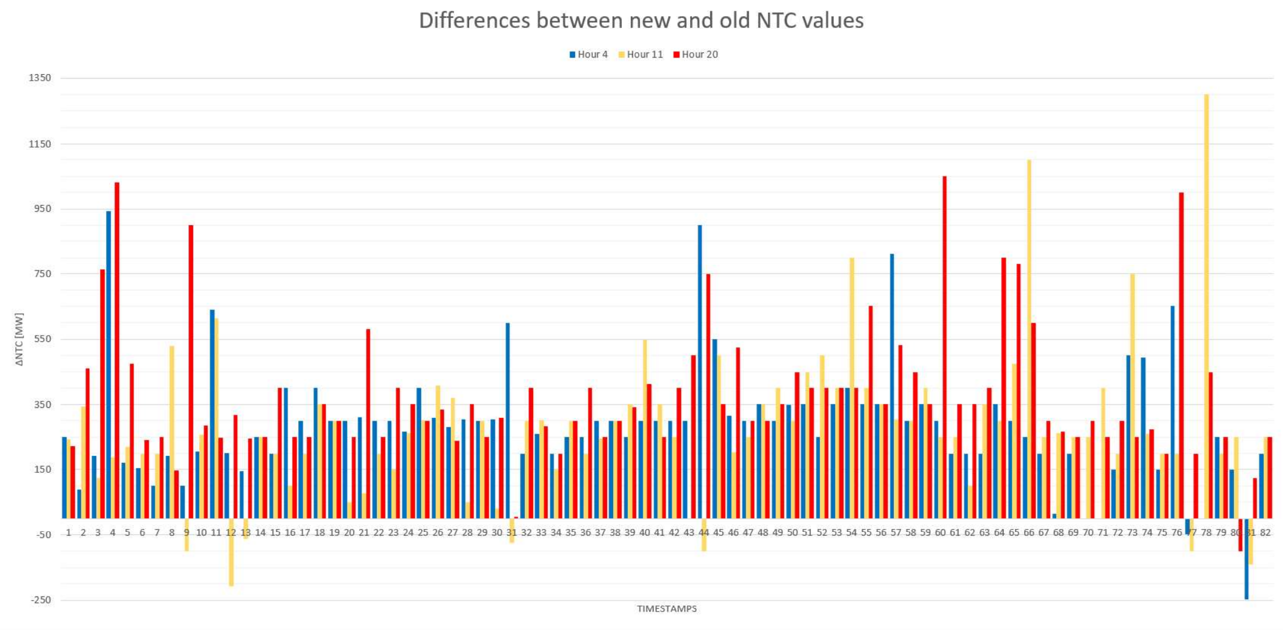

Figure 7. Differences between NTC values per hour calculated before and after update of dynamic ampacity values into IGMs

CONCLUSION

Results calculated in this paper should be taken with some reserve, because of significant approximations regarding modeling line corridor as single span and generalizing same meteorological conditions on wider area. However, calculations presented here realistically estimate impact of deployment DLR technology on system security (examined through SA) and cross-border transfer capacity (examined through NTC calculation).

It is shown that increase of ampacity is in range 22÷76 [%], gravitating to the most common 40% value. On the other hand, system security is also increased by using DLR because number of potential congestions decreased after usage of dynamic ampacity values on specific OHLs. Regarding capacity calculations, paper describes that DLR method acquire average increase of NTC values for around 35%. Area of severe NTC congestions (bottleneck) is around TS Vardište even with potential DLR technology deployment, which is clear signal that grid infrastructure should be improved in that area. Also, it is shown that bad choice of method for calculation of P_C (because it favors $\Delta\theta$ instead of v) as well as warm springs and autumns could lead to unexpected ampacity decrease on some OHLs.

General conclusion is that DLR approach could bring significant improvement to operational planning calculations of interconnected transmission systems. However, TSOs should be aware of consequences of too optimistic rating assumptions. Clearance violations, conductor annealing and elevated temperature creep are just some consequences of exceeding the conductor rated temperature [6]. Also, DLR deployments should ensure the reliability of DLR data, primarily addressing cybersecurity concerns, integrating dynamic ratings into system operations, and verifying the financial benefits of DLR systems.

Finally, we should point out that the uncertainty of every input data must be known in order to assess the uncertainty of final result – the ampacity of the line. This task is very demanding and needs a lot of theoretical and experimental work which is yet to be done.

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