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# Analysis of Voltage Stability of the Slovak Republic's Power System †

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**Abstract:** This paper studies the voltage stability of the Slovak Republic's power system (PS) based on an assessment of the PV curves. The PV curve is a tool for assessing voltage stability, and based on its shape, it is possible to determine weak and strong voltage nodes with the possibility of voltage stability reserve quantification. We present an analysis of the influence of transformers with an automatic voltage regulator (AVR) on the shape of the PV curves and on the magnitude of voltage in the PS. In general, the 400 kV/110 kV transformers equipped with AVRs are critical assets for the PS as they address voltage control in the DS. However, in the case of voltage problems in the TS, the AVR function may worsen the voltage situation across the entire PS. Therefore, we closely analyze the negative effects of the AVR on the PS operation. This impact is clearly proved, and recommendations are given for the transmission system operator (TSO) in order to maintain voltage stability. In addition, the PV curves of the pilot nodes are analyzed very accurately, thereby confirming their importance in the TS in terms of a sufficient reserve of reactive power. The study was conducted in cooperation with the TSO, Slovenská elektrizačná prenosová sústava, a.s.

**Keywords:** transmission system; voltage stability; PV curve; automatic voltage regulator (AVR); on-load tap changer (OLTC); pilot node



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## 1. Introduction

Based on Articles 38, "Dynamic stability monitoring and assessment", and 39, "Dynamic stability management", of the Commission Regulation (EU) 2017/1485 of 2 August 2017 that established guidelines on transmission system operation, the transmission system operator (TSO) is required to perform a dynamic stability assessment at least once a year to identify the stability limits and possible stability problems in the transmission system. The voltage stability of the transmission system is one of the fields for evaluation [1,2].

Voltage stability can be defined as the ability of the power system to keep the nodes' voltages within the desired limits during normal operation and after emergencies. The typical causes of voltage instability in the power system include faults, sudden load increase, and similar changes in the power system where the voltage falls uncontrollably. Voltage instability is then characterized by the failure to deliver reactive power to the power system. This can be local, but it impacts the power system as a whole. From the view of voltage stability, the transmission system is evaluated mostly based on the relationships between active and reactive power, voltages in the individual nodes, and reactive power injected into the power system. The situation worsens when considering a weakly interconnected power system that includes long transmission lines. However, there is not a general rule, and such voltage instability problems can arise even in the most strongly interconnected power systems with high loads in some specific circumstances [3,4].

Voltage stability is mainly influenced by the following factors, as widely discussed in [3–6]:

- Transmission system (TS) configuration—the number of interconnections between and lengths of individual transmission lines;
- Load and transit through the TS;
- Strategy of the voltage control (i.e., reactive power control);
- Speed of the voltage regulators;
- Load characteristics;
- Connection and characteristics of the compensation devices;
- Installed transformers with on-load tap changers (OLTCs).

The most obvious examples of voltage stability failure are blackouts, e.g., blackouts that occurred in Italy (2003) and the USA (2003), and power system collapses, e.g., those that occurred for customers of the UCTE (2006) and in Greece (2004), India (2012), etc. [7–11]. This paper will analyze the recommended operations and measures of the 400/110 kV transformer tap changer and determine its influence on voltage stability.

After the blackout in Italy in 2003, new recommendations from the UCTE stated that "The blocking of On Load Tap Changers (OLTC) of transformers in case of severe voltage drop should be accepted practice" (Recommendation 11) [7]. The blocking of the OLTCs of transformers is also mentioned in the UCTE OH Appendix 3: Operation Security [12] and Commission Regulation (EU) 2017/2196 of 24 November 2017, Article 17, "Automatic scheme against voltage collapse" [13].

As stated above, the philosophy in the case of widespread events is clear in that the blocking of the OLTCs of transformers when the voltage is falling in the TS nodes is the most basic and the simplest preventive measure for any voltage instability event. When the minimum specified voltage is achieved anywhere in the TS, the transformer regulator is blocked, and the last tap is set as continuously active. The priority and the goal of this measure is to keep the voltage in the TS nodes and, therefore, ensure the voltage stability of the superordinate system, the TS. Some papers, such as [14–17], deal with this issue by considering different manners, but the extensive and detailed results of PV curves in the comprehensive observability area (PS SR) with concrete quantification are often missing.

Therefore, this article focuses on the evaluation of voltage stability by means of the PV curves performed based on the calculation of steady states, considering two different scenarios: the load increasing in the distribution system (DS) inside the control area and the transit increasing through the transmission system (TS). Significant attention is paid to the verification, confirmation, and, especially, the quantification of the stated recommendation: the blocking of OLTCs on transformers to maintain voltage stability in the PS.

This paper is an extended version of the paper published at the 22nd International Scientific Conference on Electric Power Engineering 2022 (EPE), held in the Czech Republic [1].

## 2. Materials and Methods

Voltage stability was evaluated primarily by using PV curves that were based on load flow calculations. Steady states were calculated for gradually increasing loads in certain selected PS nodes to the point of numeric method divergence when a critical point of maximum load was achieved. This enabled us to obtain information about the maximum load of the system in order to maintain voltage stability.

The PV curves performed for each node in the TS were based on the calculations of load flow, and a gradual worsening of the steady state in the PS provided information on the critical voltage and critical load in the individual nodes of the power system. The case-worsening process was created by means of a gradual loading of the system considering two scenarios: a load increase in the 110 kV nodes in the DS and a transit increase through the Slovak Republic TS. The topology of the power system, connections of the power plant blocks, and connections of the compensating shunt reactors were not altered.

PV curves were performed using the SSTOOLS, which is a Steady-State Analysis Tool, through the Voltage Stability Analysis Module in the PSLF software.

The PV curves enabled us to establish the following:

- The voltage change profile of particular nodes with an increasing load and increasing transit, whereby it was possible to identify strong and weak nodes;
- The critical voltages important for the change of function of the transformers with AVRs in the TS/DS, e.g., regulator OLTC blocking;
- The margin for maintenance of the voltage in pilot nodes with an increasing load and increasing transit.

The evaluation of the voltage stability was possible through the steady-state computation analysis (initial base case and other worst cases), based on the following parameters:

- Voltage magnitude in the TS nodes;
- Power angle of the transmission lines;
- Estimation of the reactive power reserve in generators by identifying the operating point in the PQ diagram;
- Estimation of the reserve of the voltage stability, i.e., the "distance" from the critical point on the PV curve (Figure 1).

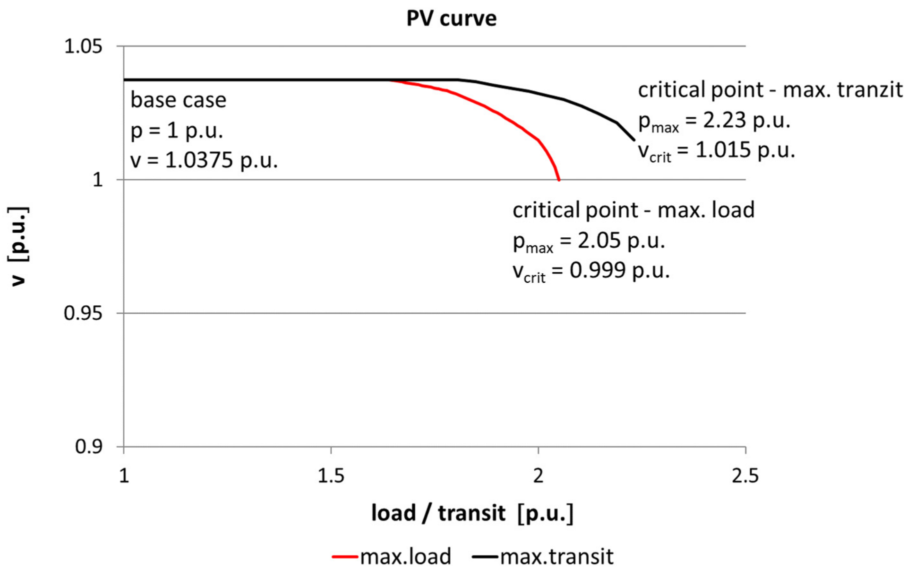


**Figure 1.** PV curve (of the node) example and explanation.

An example of the PV curve with a marked base case and two critical points for the worst cases, max. load and max. transit, is shown in Figure 1. Voltage and transit values are expressed as per-unit values. Voltage is related to the nominal voltage level of 400 kV, i.e., 1 p.u. = 400 kV. Transit is related to the transit value through the PS SR in the base case of 2216.2 MW (winter)/626.2 MW (summer), i.e., 1 p.u. = transit in the base case.

The reserve of the voltage stability is defined as follows:

$$\text{reserve} = \frac{(\text{P}_{\text{max}} - \text{P}_{\text{base case}})}{\text{P}_{\text{base case}}} \cdot 100\ \%. \tag{1}$$

The steady-state calculations were performed using standard methods: the Gauss–Seidel iterative method and the Newton–Raphson method for the European power system model. In particular, the Slovak PS was modeled down to the distribution system (110 kV) voltage level. Two estimated maximum loads and transits in Europe, from the summer and winter seasons, were taken as the initial computational states.

In this paper, the PV curves were processed from the series of steady-state simulation results considering two scenarios:

(1) Increasing the net load in the DS with the incremental step of 0.01 p.u. from the initial state, i.e., step +41 MW in winter and step +31 MW in summer. The power factor (PF)

of the loads in the PS was kept constant along with the increasing generation in the surrounding PS.

(2) Increasing the net load in the PSs of Hungary, Italy, and the Balkans with the incremental step of 0.005 p.u. from the initial state, i.e., step +443 MW in winter and step +424 MW in summer. The power factor (PF) of the loads in the PS was kept constant along with the increasing generation in northern and western Europe such that the dominant direction of the power flow through the Slovak TS was maintained.

The voltage stability reserve, as well as other parameters of the incremental steady-state computations (voltages, loads of transformers and power lines, and power angles) were taken from the initial state of the PS (load/transit), and the maximum transmitted power (load/transit) was taken from the last converged steady state.

## 3. Results

The stability assessment of any power system is usually performed for several variants in order to consider the different topology connections of the power system, power source connections, and, especially, the selected values of the power system load and transit through the power system. The real connection system, which was used in the paper, is shown in Figure 2, and can be found along with the technical specifications on the website of the TSO [18,19].

The mathematical model of the European Network TS was built based on the data provided by other European TSOs according to the agreement among the European TSOs on data exchange, which is required for various operational tasks and case studies [20]. The grid map of the TS operated by members of the European Network of the TSO is accessible from [21].

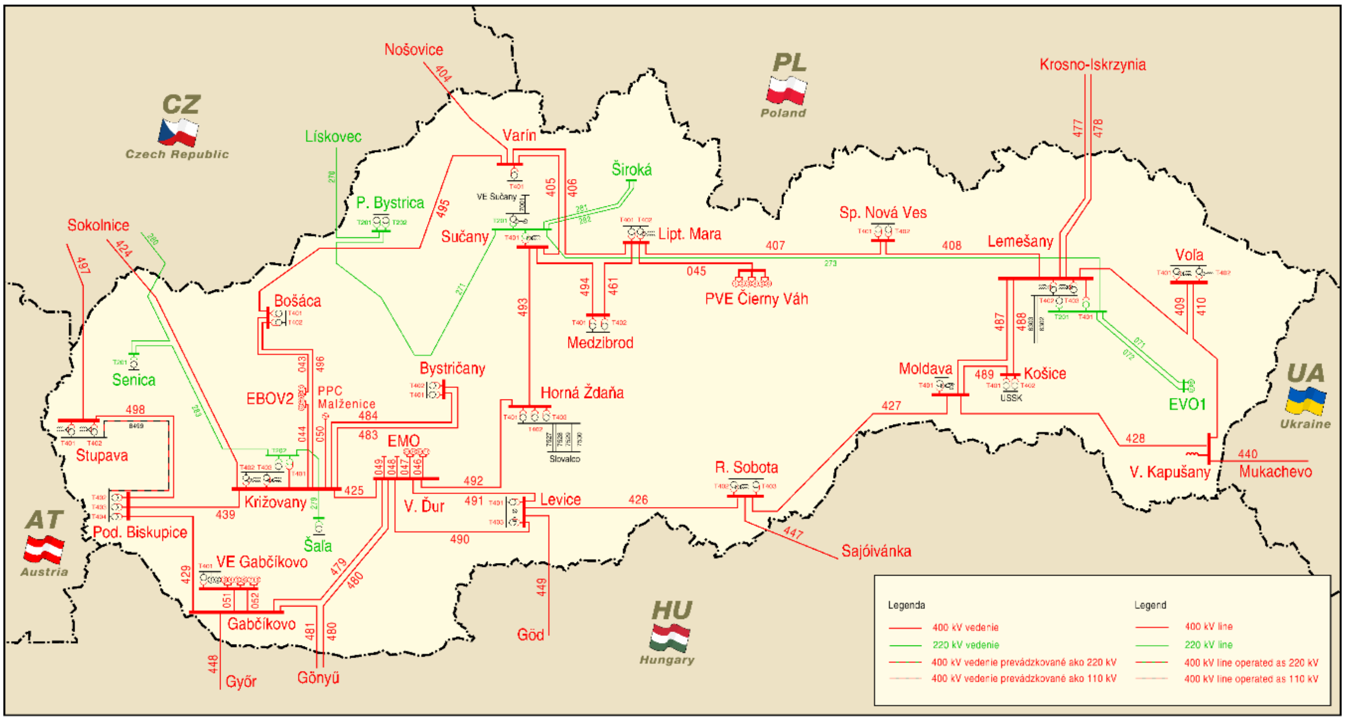


**Figure 2.** Transmission system of the Slovak Republic [22].

Within the stated analysis, we considered two initial states, winter and summer, which were based on all control area measurements in the European Network in accordance with Commission Regulation 2017/1485.

The results of the voltage stability presented in this article are valid for the basic topology of the Slovak Republic PS for the year 2022, as the loads for two different periods of the year, winter and summer, were considered (significantly different load conditions).

The load flow calculations of the initial steady state in the PS were performed by considering the AVR transformers. The 400 kV/110 kV transformers and the 220 kV/110 kV transformers were equipped with OLTCs. The aim of the AVR transformers was to control the magnitude of voltage on the 110 kV side of a transformer in the required interval. Since the transformation of the TS/DS in the electrical power system of the Slovak Republic was predominantly conducted through the 400 kV/110 kV transformers, we present the results for those transformers. Table 1 shows the results of the voltage control on transformers with the parameters of interval of the required values on the 110 kV side, tap step, and regulation extent (number of taps).

**Table 1.** List of 400/110 kV transformers with AVR control.

| Transformer | $V_{max}$ (kV) | $V_{min}$ (kV) | Step (p.u.) | Tap Min | Tap Max |
|---|---|---|---|---|---|
| T401 BOSA | 120.0 | 118.0 | 0.0133 | −9 | 9 |
| T402 BOSA | 120.0 | 118.0 | 0.0143 | −8 | 8 |
| T401 BYST | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T402 BYST | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T401 GABC | 120.0 | 118.0 | 0.0120 | −9 | 9 |
| T402 HZDA | 120.0 | 117.0 | 0.0110 | −8 | 8 |
| T403 HZDA | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T402 KOSI | 121.0 | 117.0 | 0.0126 | −8 | 8 |
| T401 KOSI | 121.0 | 117.0 | 0.0126 | −8 | 8 |
| T402 KRIZ | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T403 KRIZ | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T401 LMAR | 120.0 | 118.0 | 0.0137 | −7 | 7 |
| T402 LMAR | 120.0 | 118.0 | 0.0137 | −7 | 7 |
| T402 LEME | 120.0 | 118.0 | 0.0143 | −8 | 8 |
| T403 LEME | 120.0 | 118.0 | 0.0143 | −8 | 8 |
| T401 LEVI | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T403 LEVI | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T401 MEDZ | 120.0 | 118.0 | 0.0145 | −8 | 8 |
| T402 MEDZ | 120.0 | 118.0 | 0.0145 | −8 | 8 |
| T401 MOLD | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T402 PBIS | 120.0 | 118.0 | 0.0120 | −9 | 9 |
| T404 PBIS | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T402 RSOB | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T403 RSOB | 120.0 | 118.0 | 0.0112 | −9 | 9 |
| T401 SNV | 120.0 | 118.0 | 0.0115 | −9 | 9 |
| T402 SNV | 120.0 | 118.0 | 0.0126 | −8 | 8 |
| T401 STUP | 120.0 | 118.0 | 0.0126 | −8 | 8 |
| T402 STUP | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T401 VARI | 120.0 | 118.0 | 0.0125 | −9 | 9 |
| T401 VOLA | 120.0 | 118.0 | 0.0150 | −8 | 8 |
| T402 VOLA | 120.0 | 118.0 | 0.0150 | −8 | 8 |

The basic data from the initial steady state are listed in Table 2. In the initial state, all voltages were within the required tolerance of 400 kV +5%/−10%, 220 kV + 11,18%/−10% [2]. The allowed current was not exceeded in any of the power lines or any transformer. There was a sufficient reserve of reactive power in the overexcitation area of the generators connected in the TS.

**Table 2.** Load flow: base cases in winter and summer.

| Base Case | With AVR in Winter | With AVR in Summer |
|---|---|---|
| Total generation | 4626.9 MW | 4334.3 MW |
| Total load | 4088.7 MW (1 p.u.) | 3309.9 MW (1 p.u.) |
| Total losses | 81.5 MW | 54.4 MW |
| Losses in the TS | 52.1 MW | 31.2 MW |
| Losses in the DS | 29.4 MW | 23.2 MW |
| Power balance | 260.4 MW | 787.7 MW |
| Transit | 2216.2 MW (1 p.u.) | 626.2 MW (1 p.u.) |
| Max. loaded line | 56% (V449) | 41% (V449) |
| Max. voltage in the TS | 416.8 kV (L. Mara) | 418.0 kV (Medzibrod, L. Mara) |
| Min. voltage in the TS | 413.4 kV (H. Ždaňa) | 413.2 kV (Košice) |
| Max. power angle on the power line–tie line | 7.56° (V449) | 5.52° (V449) |
| Max. power angle on the power line–internal line | 6.80° (V426) | 5.52° (V426) |
| | All generators are in the under-excitation area, meaning a **sufficient reactive power reserve.** | |

As mentioned above, the differences in the initially modeled steady-state computations for summer and winter were mostly in the amount of transit through the TS and in the amount of load in the DS. The difference in the transit amount was approximately 1600 MW, and in the load, approximately 780 MW. The power system connection, as well as the connection of the generators, was constant through every steady-state (both seasons) computation.

### *3.1. Results of the Load Flow Calculations for the Worst States*

The results of the load flow calculations for the worst states with the maximum load in the 110 kV network with and without considering the AVR of transformers are presented in Table 3. The case-worsening process was performed by gradual increasing the load in the 110 kV network of the Slovak Republic PS and by gradual increasing the generation in other PSs of the European network. The limit of the case-worsening process—achievement of the worst state—was determined based on the divergence of the load flow calculations. It should be noted that all the loads were modeled as static load models, i.e., by means of the model: P, Q = a constant [3].

Based on the results, the following conclusions were made for the worst case with the maximum load in the DS:

- Some transmission lines were overloaded;
- Some transformers were overloaded;
- Voltages in some PS nodes were outside the permitted tolerance margin;
- The generators worked at the maximum overexcitation state.

For the state without the AVR, the steady-state divergence encountered was 2.05 times higher than the original load in winter and 2.15 times higher in summer, and with the AVR it was 2.04 times higher in winter and 2.27 times higher in summer.

**Table 3.** Load flow results: worst cases with maximum load in the DS.

| The Worst States with Maximum Load in DS | Without AVR in Winter | With AVR in Winter | Without AVR in Summer | With AVR in Summer |
|---|---|---|---|---|
| Total generation in PS | 4626.9 MW | 4626.9 MW | 4334.3 MW | 4334.3 MW |
| Total load in PS | 8381.8 MW (2.05 p.u.) | 8340.8 MW (2.04 p.u.) | 7132.9 MW (2.15 p.u.) | 7502.8 MW (2.27 p.u.) |
| Total losses in PS | 214.6 MW | 201.7 MW | 144.1 MW | 140.4 MW |
| Losses in TS | 108.8 MW | 110.7 MW | 67.1 MW | 70.0 MW |
| Losses in DS | 105.8 MW | 91.0 MW | 77.0 MW | 70.4 MW |
| Power balance | −3661.1 MW | −3627.3 MW | −3335.4 MW | −3706.2 MW |
| Transit | 770.6 MW | 770.2 MW | 452.8 MW | 440.5 MW |
| Reserve of stability | 105% | 104% | 116% | 127% |
| Max. loaded line | 123% (V404) | 123% (V404) | 80% (V270) | 80% (V270) |
| Max. voltage in TS | 410.2 kV (Gabčíkovo) | 407.9 kV (Gabčíkovo) | 414.8 kV (Gabčíkovo) | 414.5 kV (Gabčíkovo) |
| Min. voltage in TS | 371.5 kV (Horná Ždaňa) | 365.9 kV (Horná Ždaňa) | 380.8 kV (Horná Ždaňa) | 377.5 kV (Horná Ždaňa) |
| Max. power angle of the power line–tie line | 13.57° (V270) | 13.50° (V270) | 9.32° (V270) | 9.35° (V270) |
| Max. power angle of the power line–internal line | 7.63° (V426) | 7.80° (V426) | 5.65° (V426) | 5.71° (V426) |
| | All generators are in over-excitation area, meaning **no reactive power reserve.** | | | |

By comparing both modeled cases (winter and summer), it was concluded that the achieved maximum load in the DS was sufficiently higher in comparison with the initial state, whereas the relative values had approximately the same value (in absolute values, a higher maximum load was achieved for the winter season). The reserve of the static stability computed from the maximum load was high enough for all the listed evaluated states.

The impact of the AVR on these evaluated values was basically negligible. However, in the case of the AVR's impact on the voltage in the TS nodes when increasing the load in the DS, the AVR was considered to have a negative effect, as is also shown in the results in the next subsection of the paper.

Figure 3 shows the 400 kV/110 kV transformer loads for the worst cases with a maximum load with and without consideration of the AVR. There was a slight influence of OLTC activity on the transformer load.

In Table 4, the steady-state results are presented for the worst cases with a maximum transit achieved through the Slovak Republic TS with and without considering the AVR of transformers. The case-worsening process of the steady state was performed by increasing the transit through the Slovak Republic TS, gradually increasing the load in Hungary, Italy, and the Balkans, and, at the same time, gradually increasing production in the north and west of Europe. The dominant direction of the transit in the Slovak TS was from the northwest to the southeast. This was considered in the model as well.

Based on the results, the following conclusions were made for the worst case with maximum transit:

- Cross-border power lines were overloaded;
- Voltages in some PS nodes were outside the permitted tolerance margin;
- Generators worked at the maximum overexcitation state.

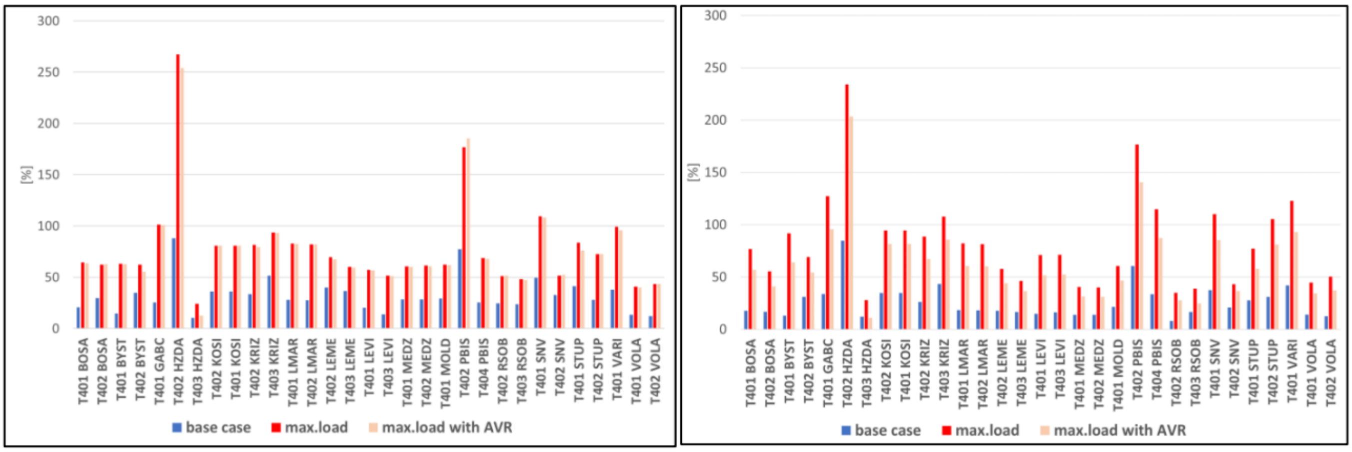


**Figure 3.** Overview of 400/110 kV transformer loads: winter (left), summer (right).

**Table 4.** Load flow results: worst cases with maximum transit through the TS.

| The Worst States with Maximum Transit through TS | Without AVR in Winter | With AVR in Winter | Without AVR in Summer | With AVR in Summer |
|---|---|---|---|---|
| Total generation in PS | 4626.9 MW | 4626.9 MW | 4334.3 MW | 4334.3 MW |
| Total load in PS | 4088.7 MW | 4088.7 MW | 3309.9 MW | 3309.9 MW |
| Total losses in PS | 225.7 MW | 236.3 MW | 159.2 MW | 154.8 MW |
| Losses in TS | 190.0 MW | 201.3 MW | 132.3 MW | 128.9 MW |
| Losses in DS | 35.7 MW | 35.0 MW | 26.9 MW | 25.9 MW |
| Power balance | 116.2 MW | 105.6 MW | 682.9 MW | 687.3 MW |
| Transit | 5321.1 MW (2.40 p.u.) | 5142.0 MW (2.32 p.u.) | 4164.4 MW (6.65 p.u.) | 4063.9 MW (6.49 p.u.) |
| Reserve of stability | 140% | 132% | 565% | 549% |
| Max. loaded line | 135% (V404) | 136% (V404) | 99% (V404) | 96% (V404) |
| Max. voltage in TS | 410.6 kV (Bystričany) | 388.3 kV (Bystričany) | 415.2 kV (Bystričany) | 415.6 kV (Bystričany) |
| Min. voltage in TS | 371.6 (V. Kapušany) | 345.1 (V. Kapušany) | 380.5 (V. Kapušany) | 376.5 (V. Kapušany) |
| Max. power angle of the power line–tie line | 15.04° (V449) | 17.04° (V449) | 13.40° (V449) | 13.29° (V449) |
| Max. power angle of the power line–internal line | 8.43° (V426) | 9.66° (V426) | 6.87° (V426) | 6.89° (V426) |
| | All generators are in over-excitation areas, meaning **no reactive power reserve.** | | | |

For the state where the AVR was not considered, the steady-state divergence encountered was 1.16 times higher than the original load in winter and 1.195 times higher in summer. The transit through the Slovak Republic TS increased to be 2.4 times higher in winter and 6.65 times higher in summer.

For the state when considering the AVR, the steady-state divergence encountered was 1.155 times higher than the original load in winter and 1.19 times higher in summer. The transit through the Slovak Republic TS increased to be 2.32 times higher in winter and 6.49 times higher in summer.

By comparing both modeled cases (winter and summer), it was concluded that the achieved maximum transit through the TS had much higher p.u. values in the summer season, but in absolute values, the maximum transit through the TS was achieved in the winter season. The stated difference was caused by a much lower value of the initial TS transit. Therefore, the values through which the results are interpreted must be chosen carefully.

The impact of the AVR on these evaluated values, similar to the load increase scenario, was not significant. However, regarding its impact on the voltage in the TS nodes when increasing the transit, the AVR was considered to have a negative effect, as is also shown in the results in the next subsection of the paper.

Figure 4 shows the position of the OLTC taps on the 400 kV/110 kV transformers for the analyzed states when considering transformers with the AVR. The results clearly indicate that some transformers in the worst cases achieved marginal taps.

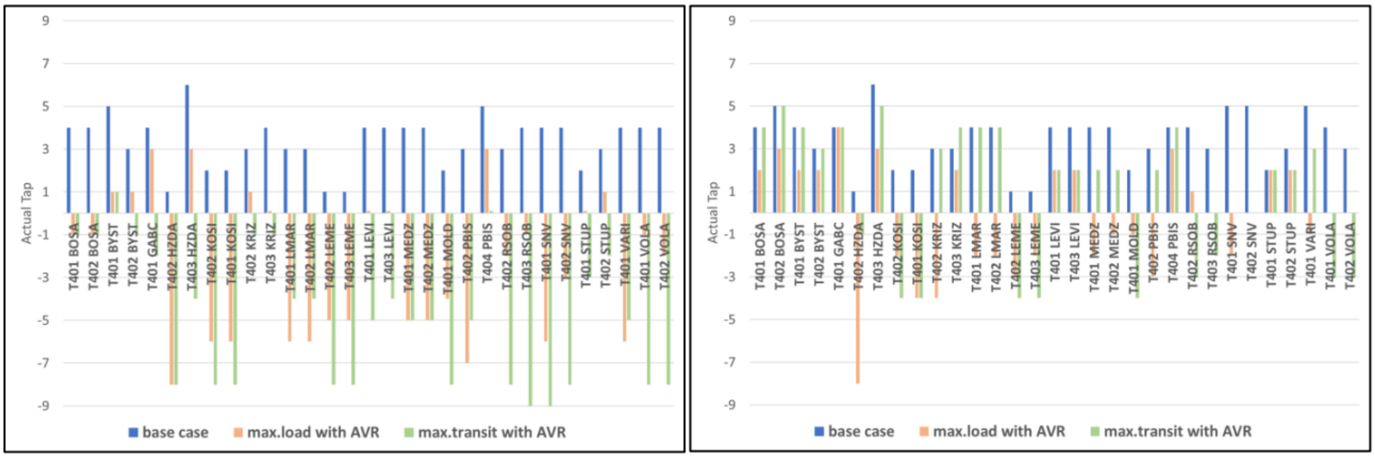


**Figure 4.** Position of OLTC taps on the 400 kV/110 kV transformers: winter (left), summer (right).

Figure 5 shows the magnitude of the voltage in the 400 kV substations for particular states. The negative influence of the AVR on the voltage in the PS nodes was immediate in this situation; when regulating the voltage on the DS transformer side, the voltage drop in the TS nodes was significantly higher compared to the application of the AVR. The most significant voltage drops were in the winter season. In the summer season, there was a lower load in the PS and lower transit in the PS; thus, the power lines were also under a lower loading, which meant this situation was favorable in terms of the reactive power balance on the power lines. The adverse impact of the AVR was also visible in the shape of the PV curves. The PV curves of states when considering the AVR were lower in comparison to the PV curves without the AVR, and their shape was steeper, especially for voltage-weak nodes (characterized by no or a minimal possibility of voltage control).

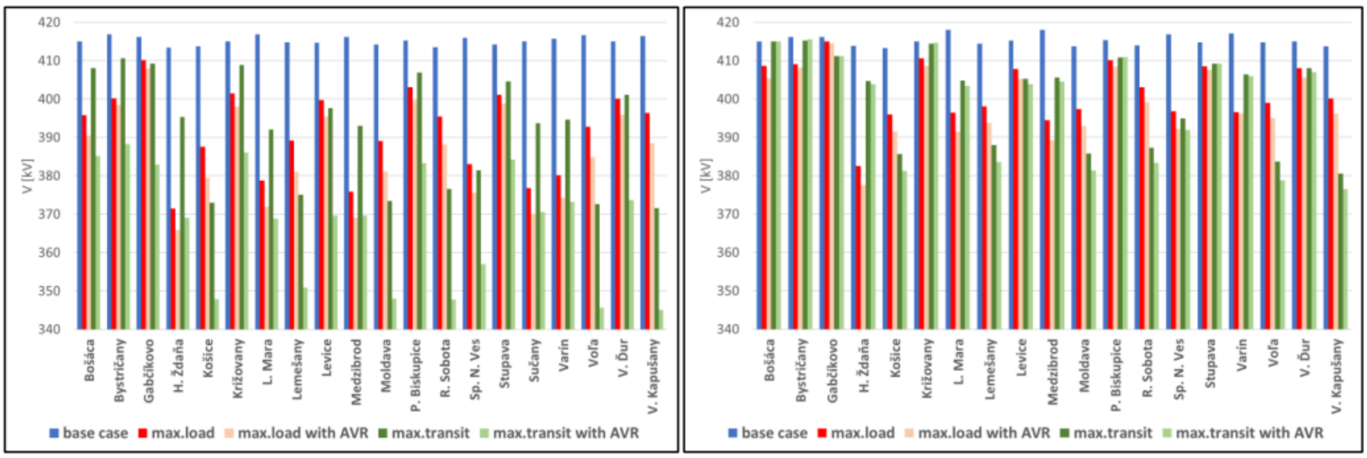


**Figure 5.** Voltage in 400 kV TS substations: winter (left), summer (right).

Figure 6 shows the magnitudes of voltage in the 110 kV substations for particular states. In the modeled scenarios, when considering the AVR in winter and when the voltage control on the DS transformer side was enabled, there were still some DS nodes not sufficiently controlled to achieve their initial voltage level because the transformers were already on their last possible tap; therefore, they lost the ability to control voltage in that direction.

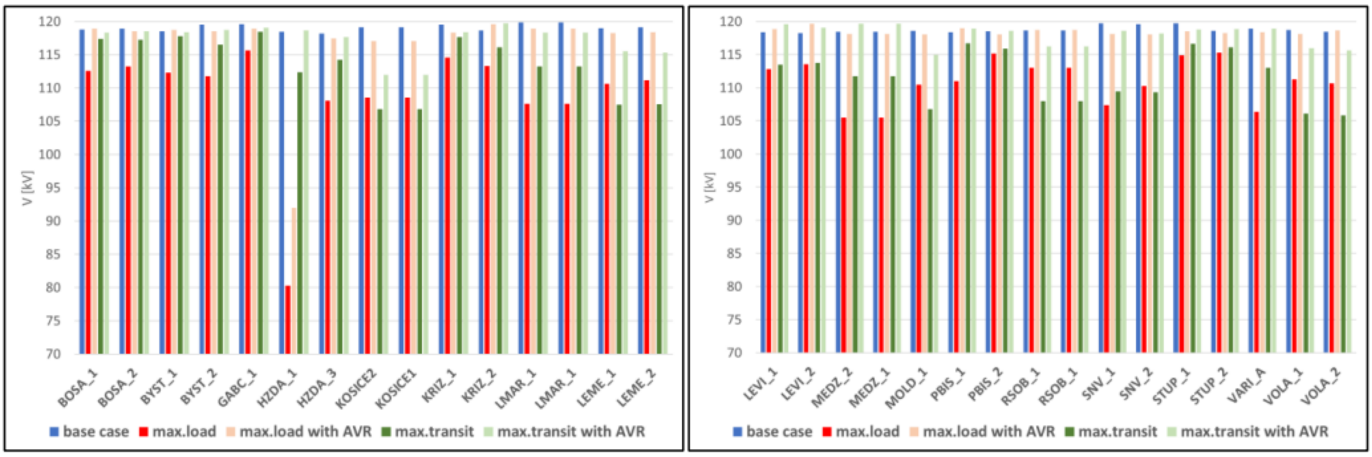


**Figure 6.** Voltage in 110 kV DS substations: winter.

Figure 7 shows the magnitudes of voltage in the 110 kV substations for individual states in the summer. The maximum range of the voltage control of transformers in summer was set to be sufficient for the application of the AVR to achieve the desired voltage levels on the DS side.

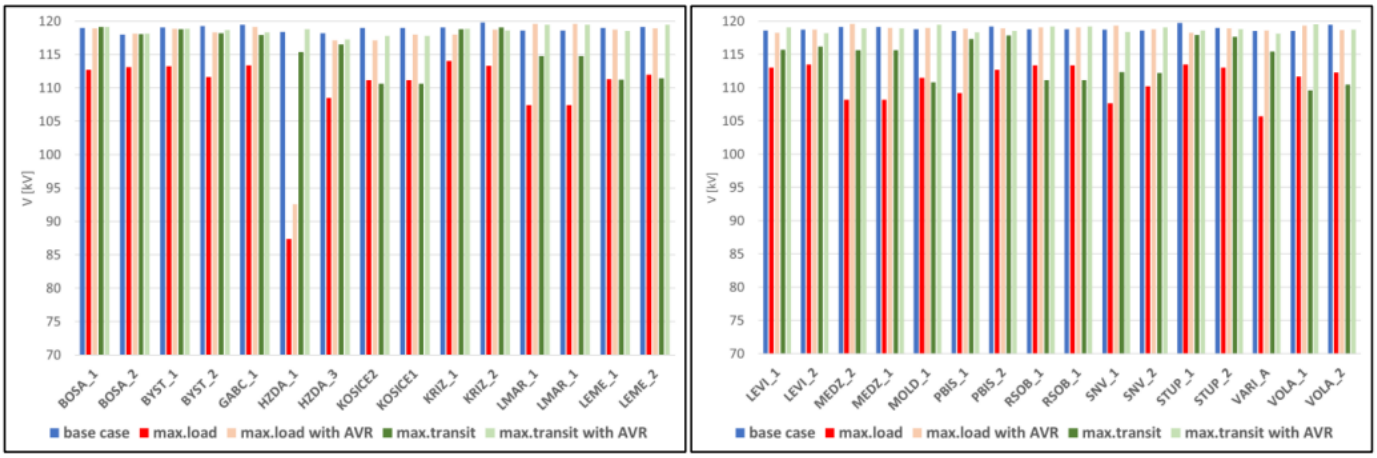


**Figure 7.** Voltage in 110 kV DS substations: summer.

Summary data on transformers and voltages are stated in the tables in Appendix A, including actual OLTC taps, loads of transformers, and voltages on the 400 kV and 110 kV sides. For the worst case without the AVR, the tap position was the same as in the initial state. The load of the transformers was approximately the same for the worst case of the maximum transit as in the initial state. The voltage in the TS nodes for the worst-case scenario with a maximum load or maximum transit was considered to be the critical value of voltage from the PV curves, i.e., it represented the point of the PV curve where the voltage was minimum while the load was at the maximum (in this paper, it equaled the load in the DS or the transit through the TS).

The red color in the table indicates the marginal taps achieved for the transformers and voltages at the 110 kV side of the transformers that did not achieve the required value when considering the AVR. The results indicate that the voltage on the 110 kV side of the transformers was significantly lower than the required value in the worst case without the AVR.

The voltages in the TS nodes that exceeded the boundary values (400 kV +5%/−10%) are colored red as well. It should be noted that the lower voltage levels in the TS nodes were observed for the worst-case scenario with the maximum transit and that voltage levels under the allowed 360 kV were also observed with the active AVR system. In the summer, the TS node voltages were within the boundary values as a result of the light load of the power lines in the TS, and therefore, a favorable state for a reactive power balance in the power lines existed.

*3.2. PV Curves for Selected Nodes of TS of the Slovak Republic*

PV curves were performed for each node of the Slovak Republic's TS on the basis of load-flow calculations with the gradual worsening of the steady state in the power system. Two scenarios were considered: an increase in the load in the 110 kV networks and an increase in the transit through the Slovak Republic TS.

The shape of the PV curves enabled us to identify the voltage-strong or voltage-weak nodes, i.e., those more or less dependent on increasing the load or transit, which were the pilot nodes (substations) and nodes electrically close to them. On the other hand, the steeper shapes of the PV curves were characteristic of voltage-weak nodes. Figures 8–12 include the PV curves for the selected nodes. It is necessary to emphasize that the proportionate load and proportionate transit (x-axis) define a significantly different modeled situation in the PS. The largest differences were observed mostly for the results from the summer season, specifically in the p.u. values of the load and transit.

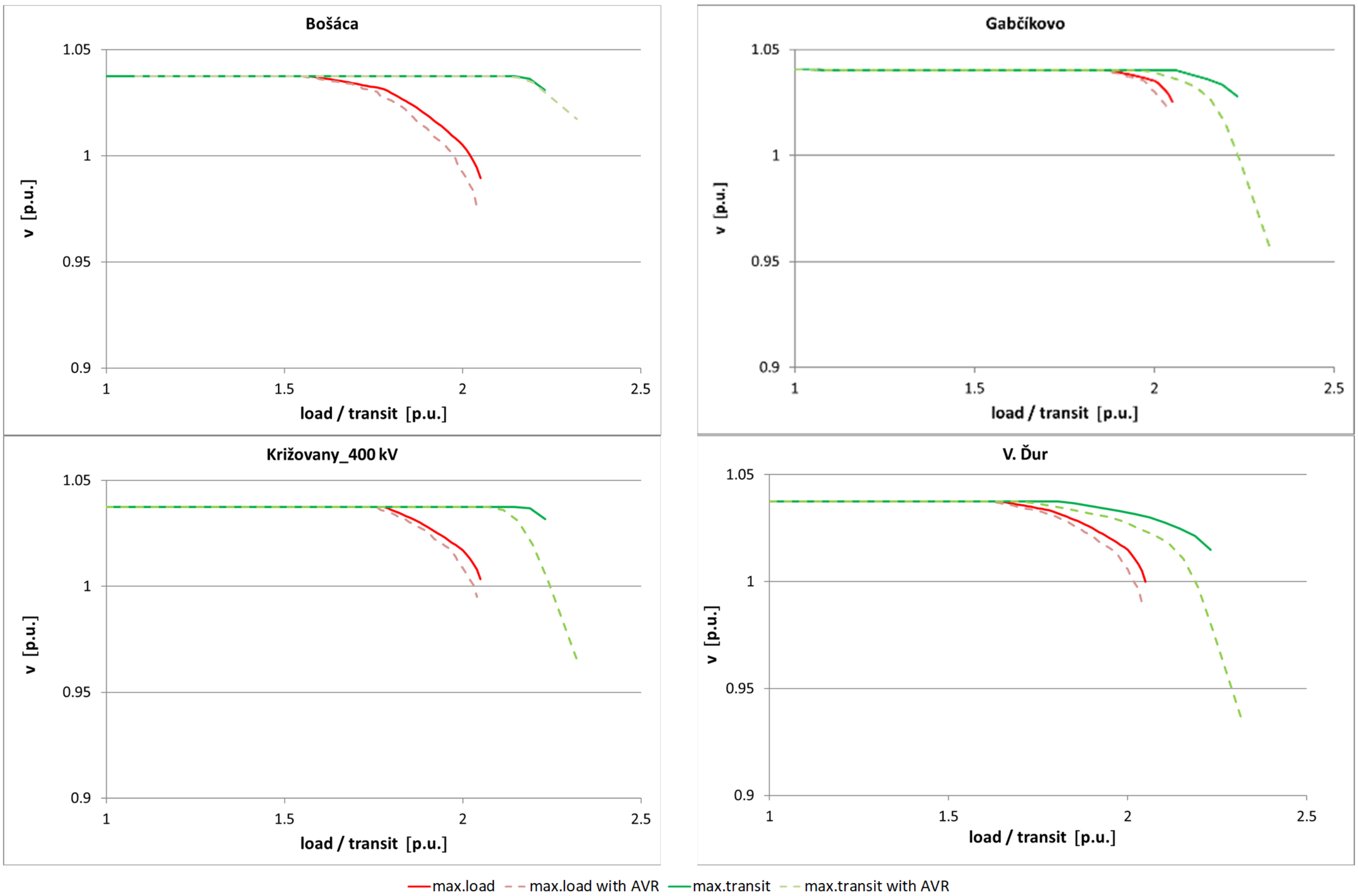


**Figure 8.** PV curves for the pilot nodes in the TS: winter.

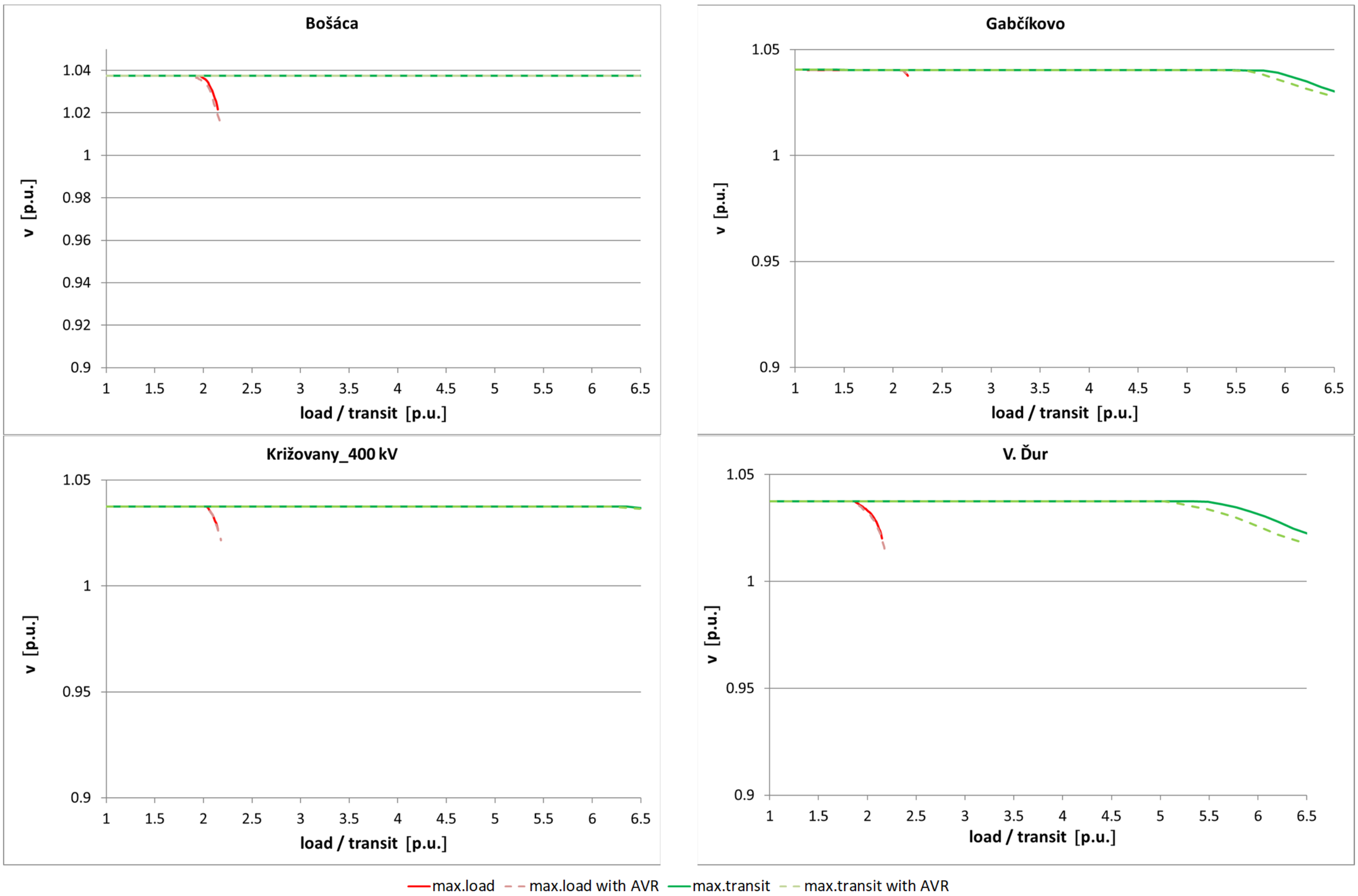


**Figure 9.** PV curves for the pilot nodes in the TS: summer.

### 3.2.1. Pilot Nodes

Pilot nodes in the TS are essential for voltage control and for the surrounding electrical area in the power system. The placement of the pilot node is dependent mostly on the voltage control capabilities in the node (substation), i.e., it is necessary to consider most of the flexible compensation devices installed (e.g., synchronous generators, FACTS, rotating compensators, etc.) [23]. In the Slovak Republic's TS, the main compensation devices are the synchronous generators, which is why the pilot nodes are found in the western part of the country, where most of the power generation is connected. Although the PS itself is relatively tightly interconnected and the national transmission lines are mostly under a light load (favorable reactive power balance and prevailing capacitive load on the power lines), the voltage in the TS nodes tends to be higher; therefore, simple shunt reactors are utilized when needed.

Figures 8 and 9 illustrate the PV curves for the pilot nodes in the TS (V. Ďur, Križovany, Bošáca, and Gabčíkovo) in the winter and summer, with and without the AVR application. The two scenarios of the increasing load and transit were analyzed. There is a visible knee point on the PV curves when electrically close generators lost their voltage control ability, i.e., they were on the margin of the maximum overexcitation state.

The value of the reserve of the reactive power control in the pilot node had a significant influence on its PV curve shape. The reactive power amounts of generators in an overexcitation state for the pilot nodes is shown in Table 6.

Table 5 presents the values of proportionate load and transit, where the change in ability to maintain voltage in the pilot node occurred.

**Table 5.** Relative values of load and transit: loss of ability to maintain voltage in the pilot nodes.

| Pilot Node | Max. Load | | Max. Transit | |
|---|---|---|---|---|
| | **Without AVR Winter/Summer** | **With AVR Winter/Summer** | **Without AVR Winter/Summer** | **With AVR Winter/Summer** |
| Bošáca | 1.58/1.94 | 1.58/1.90 | 2.16/6.65 | 2.16/6.49 |
| Gabčíkovo | 1.87/2.01 | 1.87/2.01 | 2.01/5.62 | 1.99/5.78 |
| Križovany | 1.78/2.04 | 1.78/2.03 | 2.16/6.49 | 2.07/6.20 |
| V. Ďur | 1.65/1.87 | 1.62/1.86 | 1.86/5.49 | 1.70/5.19 |

**Table 6.** Reactive power of the generators in the overexcitation area of the PQ diagram.

| Pilot Node | Qgen (MVAr) |
|---|---|
| Bošáca | 160 |
| Gabčíkovo | 240 |
| Križovany | 160 |
| V. Ďur | 320 |

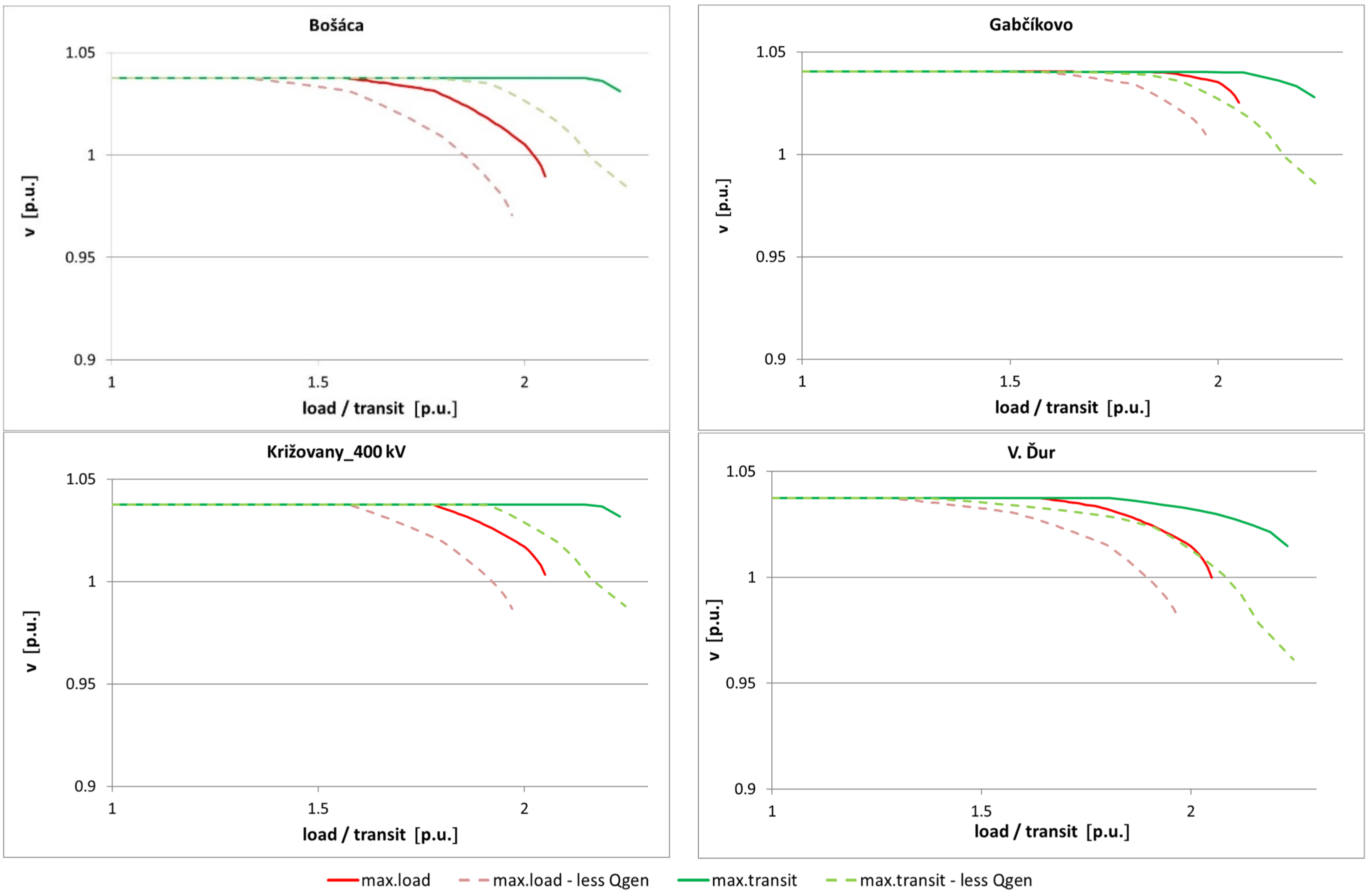


**Figure 10.** PV curves for the pilot nodes in the TS in winter; less $Q_{GEN}$ in overexcitation area.

The reserve of the reactive power control was the highest in pilot node "V. Ďur", even though the breakpoint of the PV curve occurred earlier than in other pilot nodes. This indicates that the PV curve shape was also influenced by other factors, such as how well the pilot node is interconnected with the TS, how the node was influenced by the load in the DS, and how the voltage level in this node was affected by the amount of transit through the TS.

In Figure 10, the PV curves represent the narrowed generator PQ diagrams in the overexcitation area (where the amount of available reactive power was halved), which were controlling the voltage in the nodes. The computations were performed for the winter season and without the application of the AVR. It can be seen that there was a visible difference in the PV curves where the knee point occurs. This clearly indicates that generators need to have a wide enough PQ diagram to ensure the sufficient reserve of the reactive power control in the TS.

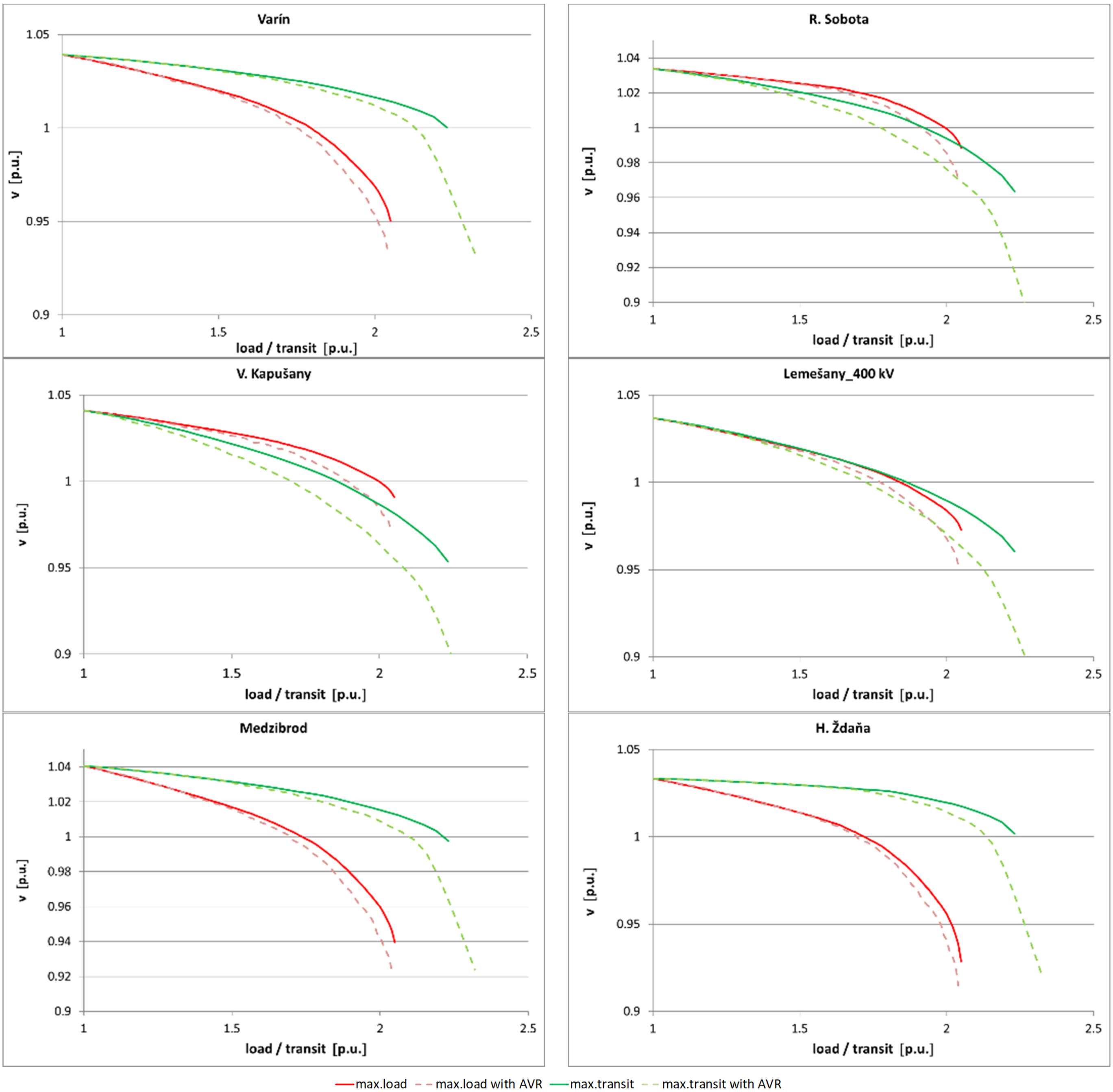


**Figure 11.** PV curves for selected nodes in the TS: winter.

### 3.2.2. Voltage-Weak Nodes

Figures 11 and 12 contain the PV curves, but this time, for the selected voltage-weak nodes in the TS. Their shape is visibly steeper, which means the voltage was highly dependent on the active load (given the increasing load or transit). Some nodes were more dependent on the load increase in the DS (Medzibrod and H. Ždaňa), some on the increasing transit (V. Kapušany), and some on both scenarios. The reason for this behavior was due to the different connections of the node in the PS, the number of connected transformers in the node, and the placement of the international transit within the PS.

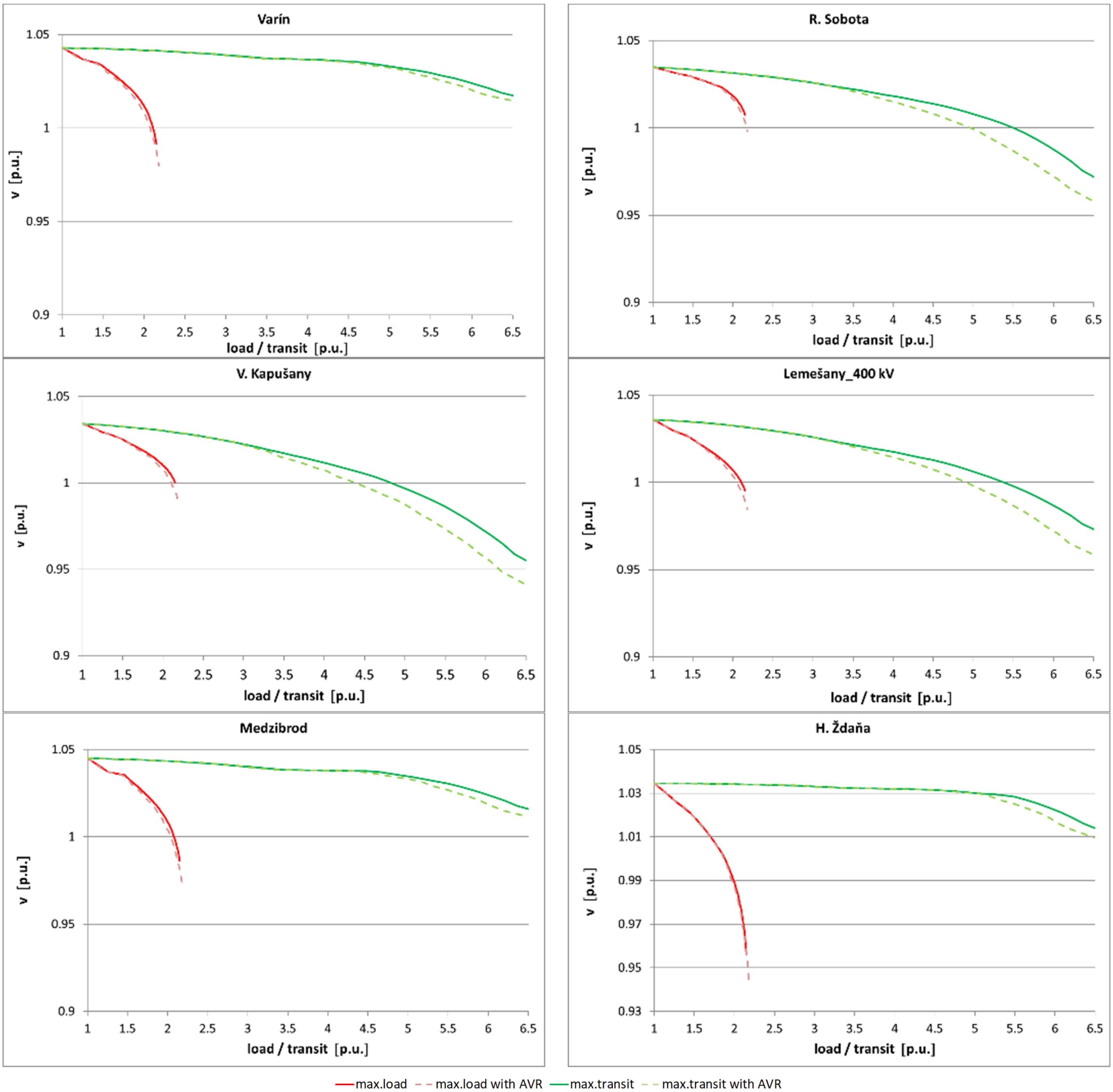


**Figure 12.** PV curves for selected nodes in the TS: summer.

*3.3. Fixing Critical Voltage Values in Nodes of the TS of the Slovak Republic to Block OLTCs on Transformers*

The basic and simplest preventive measure to avoid the initiation of voltage instability or voltage collapse is to block the OLTCs on TS/DS transformers by increasing the voltage in the TS nodes. Conditions for blocking the 400 kV/110 kV and 220 kV/110 kV transformers with the AVR can be specified on the basis of the PV curves.

From the perspective of voltage stability or the prevention of voltage instability initiation, it is necessary to block the OLTC before the critical voltage value is reached in the substation on the side of the TS, which is represented by the peak of the PV curve.

Other possible solutions when there is a decrease in the PS nodes include [23,24]:

- The change—such as a decrease in the required values of regulated voltage on the secondary side of the transformers—in the DS, whereby the OLTC on the transformer will continue operate;
- The setting of a particular tap on the transformer and blocking it in the given position;
- The reverse logic of tap switching, which is the switching of the taps controlled according to the voltage in the TS nodes, not the voltage value in the DS. It is possible to divide the transformers into groups controlled on the basis of voltage in the defined TS nodes. In this case, various types of transformers in the TS must be considered from the point of view of the tap-winding location [25].

In systems with problems in the field of voltage stability, specific schemes of protection are used that include the activity of regulators on generators, the control of transformer tap-switching from the lowest voltage levels to the highest ones (increase in the total regulation range of transformer ratios), and group control to switch transformer taps until under-voltage load shedding occurs [26].

The values of critical voltages in individual TS nodes in the Slovak Republic's PS are not the same (see Tables A1–A4 in Appendix A). In addition, the critical values from the load-flow calculations under the scenarios of a load increase and transit increase are not the same. It is obviously not possible to reset the values for OLTC blocking on the transformers with every change in the system topology or change in load.

The results clearly indicate that the maximum critical voltage value in some 400 kV substations was higher than the nominal voltage. This may be a consequence of the sufficient control of reactive power in the generators and an excessive capacity for charging power in the transmission lines. This implied that the size of the voltage is not the only indicator of possible problems with voltage stability. Therefore, it is necessary to set OLTC blocking to the nominal voltage as a minimum for each node of the TS. This proposal was seconded by the fact that during the normal operation of the PS, voltages in the TS nodes were close to the maximum-allowed voltage value (420 kV), and in a case where the voltage in the nodes falls close to the nominal value, such a situation may be considered serious. Setting the OLTC blocking at the nominal voltage value $V_n$ in the TS node constitutes a sufficient reserve from the point of view of voltage stability.

## 4. Conclusions

Based on our analysis of the voltage stability of the Slovak Republic's PS, we concluded that it is voltage stable (the defined voltage stability reserve was sufficient at over 100%). This corresponds to the fact that during normal operation, the generators connected to the Slovak Republic's TS operate predominantly in the area of underexcitation, and shunt reactors are used to compensate in the TS.

The case-worsening process: An increase in the load and increase in the transit were performed without a topology change of the Slovak Republic's PS, i.e., even the connection of the shunt reactors was not changed. With a decrease in voltage in the TS nodes, the first measure would be to switch-off the shunt reactors, which would shift the margins of voltage stability, and the reserve would be higher.

The sufficient reserve of voltage stability in the Slovak Republic's PS was noted in the shape of the PV curves of the pilot nodes. The breakpoint of the PV curves, that is, the loss of the generators' regulation ability to maintain voltage in the pilot nodes in the TS, was achieved by a relatively high load and transit in the PS (Table 5). However, it was important to keep a sufficient reserve of the reactive power control in the generators (in terms of the voltage stability, mostly in the overexcitation area), as indicated in Figure 10.

The analysis of the application of an AVR suggested that the voltage control when increasing the load in the DS, as well as when increasing the transit through the TS, had a negative effect on the TS node voltage. To maintain the voltage stability of the PS, a simple measure must be utilized: the blocking of the OLTC devices when the voltage drops in the TS. However, we cannot state the exact voltage level at which this measure should be applied on a general scale regarding the PS, at least not from the analysis carried out in this paper. The critical voltage is different even for a single node, given the actual circumstances: the initial load in the node, the current transit in the PS, the power system topology, and the current synchronous generator operating points in their PQ diagrams. After discussions with the Slovak TSO, it was determined that the minimum voltage value in the TS nodes, which activates the OLTC blocking of the transformers, would be the nominal voltage in that node.

In summary, we can make the following recommendations to ensure the voltage stability of the Slovak Republic's PS:

- Preserve the number of pilot nodes in the PS.
    - The positive impact of the pilot nodes on the electrically closest substation was obvious from the shape of the PV curves. Therefore, we recommend that the number of pilot nodes in the Slovak Republic's TS be preserved.
- Request a sufficient regulation range of the reactive power of the sources connected to the Slovak Republic's TS.
    - It is necessary to continue ensuring that the regulation range of reactive power for generators remains unchanged and to request that new power sources connected to the TS have a sufficient regulation range of the reactive power in the areas of underexcitation and overexcitation, which means maintaining the existing policy regarding requirements for the PQ diagrams for the existing generators and new power sources.
- Maintain the voltage in the nodes in the Slovak Republic's PS to be the upper part of the range of the permitted values, i.e., between the 220 kV and 400 kV voltage levels.
- Block the OLTCs on the 400 kV/110 kV transformers and 220 kV/110 kV transformers as a preventive measure in case of a decrease in voltage in the TS nodes.
    - The comparison of states with an AVR on transformers and without an AVR proved the negative impact of voltage control on transformers in states of emergency, such as when there is a high load or a high transit in the voltage in the PS nodes.

This voltage stability analysis can be further extended by applying other scenarios of gradually worsening steady states. This allows for the creation of the PV curves to assess the voltage situation in the operational state of the PS, e.g., the load increasing only in selected nodes, considering a different load power factor, or including the automatic switching on/off of compensating elements (shunts, capacitors, etc.).

There are several areas where we see potential research directions regarding the comprehensiveness of the voltage stability assessment:

- Analysis of the influence of voltage-dependent loads in the PS;
- Comparing and determining the influence of the different types of modeled loads on the PS operation by considering the voltage instability margin;
- Assessment of the significance of topological changes in the PS, i.e., the impact of planned/unplanned power line outages [21];
- Comparing the results with a modal analysis to determine the participation factors for nodes and power lines;
- Analysis of using an online voltage stability assessment [22] and the relevant evaluation of these methods;
- Comparing the results of voltage stability assessments using case studies and online methods.

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## Appendix A. Summary Data for Transformers and Voltages

**Table A1.** Summary data for transformers and voltages in winter: maximum load study.

| TS Node | DS Node | TR | Base Case | | | | Max. Load | | | Max. Load with AVR | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | V1 (kV) | V2 (kV) | Act. Tap | TR Load (%) | V1 (kV) | V2 (kV) | TR Load (%) | V1 (kV) | V2 (kV) | Act. Tap | TR Load (%) |
| Bošáca | BOSA_1 | TBO_1 | 415.0 | 118.8 | 4 | 20.6 | 395.8 | 112.6 | 64.6 | 390.5 | 118.9 | −1 | 63.5 |
| | BOSA_2 | TBO_2 | | 118.9 | 4 | 29.6 | | 113.2 | 62.1 | | 118.5 | −1 | 62.8 |
| Bystričany | BYST_1 | TBY_1 | 416.8 | 118.5 | 5 | 14.7 | 400.2 | 112.3 | 63.2 | 398.4 | 118.7 | 1 | 62.6 |
| | BYST_2 | TBY_2 | | 119.5 | 3 | 35.0 | | 111.7 | 62.4 | | 118.5 | 1 | 55.5 |
| Gabčíkovo | GABC_1 | TGA_1 | 416.2 | 119.6 | 4 | 25.2 | 410.2 | 115.7 | 101.4 | 407.9 | 118.9 | 3 | 100.7 |
| H. Ždaňa | HZDA_1 | THZ_1 | 413.4 | 118.4 | 1 | 87.8 | 371.5 | 80.3 | 267.4 | 365.9 | 92.0 | −8 | 254.0 |
| | HZDA_3 | THZ_2 | | 118.2 | 6 | 10.5 | | 108.1 | 24.2 | | 117.4 | 3 | 12.6 |
| Košice | KOSICE2 | TKO_1 | 413.7 | 119.1 | 2 | 36.0 | 387.5 | 108.6 | 80.8 | 379.5 | 117.0 | −6 | 80.5 |
| | KOSICE1 | TKO_2 | | 119.1 | 2 | 36.0 | | 108.6 | 80.8 | | 117.0 | −6 | 80.5 |
| Križovany | KRIZ_1 | TKR_1 | 415.0 | 119.5 | 3 | 33.5 | 401.4 | 114.6 | 81.5 | 398.0 | 118.3 | 1 | 79.6 |
| | KRIZ_2 | TKR_2 | | 118.6 | 4 | 51.4 | | 113.3 | 93.6 | | 119.6 | 0 | 93.3 |
| L. Mara | LMAR_1 | TLM_1 | 416.8 | 119.9 | 3 | 27.9 | 378.8 | 107.6 | 83.0 | 371.9 | 118.9 | −6 | 82.6 |
| | LMAR_1 | TLM_2 | | 119.9 | 3 | 27.6 | | 107.6 | 82.1 | | 118.9 | −6 | 81.8 |
| Lemešany | LEME_1 | TLE_1 | 414.8 | 119.0 | 1 | 40.1 | 389.1 | 110.6 | 69.7 | 381.1 | 118.2 | −5 | 67.2 |
| | LEME_2 | TLE_2 | | 119.1 | 1 | 36.5 | | 111.2 | 59.9 | | 118.4 | −5 | 59.3 |
| Levice | LEVI_1 | TLV_1 | 414.7 | 118.4 | 4 | 20.3 | 399.7 | 112.8 | 57.3 | 395.5 | 118.9 | 0 | 56.7 |
| | LEVI_2 | TLV_2 | | 118.2 | 4 | 13.9 | | 113.5 | 51.6 | | 119.7 | 0 | 51.0 |
| Medzibrod | MEDZ_2 | TME_1 | 416.2 | 118.4 | 4 | 28.2 | 375.8 | 105.5 | 60.6 | 369.1 | 118.1 | −5 | 59.9 |
| | MEDZ_1 | TME_2 | | 118.4 | 4 | 28.5 | | 105.5 | 61.2 | | 118.1 | −5 | 60.5 |
| Moldava | MOLD_1 | TMO_1 | 414.2 | 118.6 | 2 | 29.2 | 389.1 | 110.5 | 62.2 | 381.1 | 118.0 | −4 | 62.0 |
| P. Biskupice | PBIS_1 | TPB_1 | 415.3 | 118.4 | 3 | 77.1 | 403.1 | 111.0 | 176.9 | 399.7 | 119.0 | −7 | 185.2 |
| | PBIS_2 | TPB_2 | | 118.5 | 5 | 25.3 | | 115.1 | 68.6 | | 118.0 | 3 | 67.9 |
| R. Sobota | RSOB_1 | TRS_1 | 413.5 | 118.6 | 3 | 24.6 | 395.4 | 113.0 | 51.1 | 388.2 | 118.7 | −2 | 51.6 |
| | RSOB_1 | TRS_2 | | 118.6 | 4 | 23.5 | | 113.0 | 48.1 | | 118.7 | −1 | 47.4 |
| Sp. N. Ves | SNV_1 | TSN_1 | 415.9 | 119.7 | 4 | 49.6 | 383.1 | 107.3 | 109.5 | 375.5 | 118.1 | −6 | 108.3 |
| | SNV_2 | TSN_2 | | 119.6 | 4 | 32.8 | | 110.2 | 51.7 | | 118.1 | −3 | 52.3 |
| Stupava | STUP_1 | TST_1 | 414.2 | 119.7 | 2 | 41.4 | 401.1 | 114.9 | 83.5 | 398.8 | 118.5 | 0 | 75.9 |
| | STUP_2 | TST_2 | | 118.6 | 3 | 27.9 | | 115.3 | 72.6 | | 118.2 | 1 | 72.7 |
| Varín | VARI_A | TVA_1 | 415.7 | 118.9 | 4 | 37.9 | 380.2 | 106.4 | 99.3 | 374.2 | 118.4 | −6 | 95.6 |
| Voľa | VOLA_1 | TVO_1 | 416.6 | 118.7 | 4 | 13.4 | 392.7 | 111.3 | 41.0 | 384.9 | 118.1 | −1 | 40.1 |
| | VOLA_2 | TVO_2 | | 118.4 | 4 | 11.9 | | 110.7 | 43.5 | | 118.6 | −2 | 43.4 |

**Table A2.** Summary data for transformers and voltages in winter: transit study.

| TS Node | DS Node | TR | Base Case | | | | Max. Transit | | Max. Transit with AVR | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | V1 (kV) | V2 (kV) | Act. Tap | TR Load (%) | V1 (kV) | V2 (kV) | V1 (kV) | V2 (kV) | Act. Tap |
| Bošáca | BOSA_1 | TBO_1 | 415.0 | 118.8 | 4 | 20.6 | 408.1 | 117.4 | 385.1 | 118.3 | −1 |
| | BOSA_2 | TBO_2 | | 118.9 | 4 | 29.6 | | 117.2 | | 118.5 | −1 |
| Bystričany | BYST_1 | TBY_1 | 416.8 | 118.5 | 5 | 14.7 | 410.6 | 117.8 | 388.3 | 118.4 | 1 |
| | BYST_2 | TBY_2 | | 119.5 | 3 | 35.0 | | 116.5 | | 118.7 | −1 |
| Gabčíkovo | GABC_1 | TGA_1 | 416.2 | 119.6 | 4 | 25.2 | 409.2 | 118.4 | 382.9 | 119.1 | −2 |
| H. Ždaňa | HZDA_1 | THZ_1 | 413.4 | 118.4 | 1 | 87.8 | 395.3 | 112.4 | 369.0 | 118.7 | −8 |
| | HZDA_3 | THZ_2 | | 118.2 | 6 | 10.5 | | 114.3 | | 117.6 | −4 |
| Košice | KOSICE2 | TKO_1 | 413.7 | 119.1 | 2 | 36.0 | 373.0 | 106.8 | 347.8 | 111.9 | −8 |
| | KOSICE1 | TKO_2 | | 119.1 | 2 | 36.0 | | 106.8 | | 111.9 | −8 |
| Križovany | KRIZ_1 | TKR_1 | 415.0 | 119.5 | 3 | 33.5 | 408.9 | 117.7 | 386.0 | 118.4 | −1 |
| | KRIZ_2 | TKR_2 | | 118.6 | 4 | 51.4 | | 116.1 | | 119.7 | −1 |
| L. Mara | LMAR_1 | TLM_1 | 416.8 | 119.9 | 3 | 27.9 | 392.1 | 113.2 | 368.8 | 118.3 | −4 |
| | LMAR_1 | TLM_2 | | 119.9 | 3 | 27.6 | | 113.2 | | 118.3 | −4 |
| Lemešany | LEME_1 | TLE_1 | 414.8 | 119.0 | 1 | 40.1 | 375.1 | 107.5 | 350.8 | 115.5 | −8 |
| | LEME_2 | TLE_2 | | 119.1 | 1 | 36.5 | | 107.5 | | 115.3 | −8 |
| Levice | LEVI_1 | TLV_1 | 414.7 | 118.4 | 4 | 20.3 | 397.6 | 113.5 | 369.6 | 119.6 | −5 |
| | LEVI_2 | TLV_2 | | 118.2 | 4 | 13.9 | | 113.7 | | 119.1 | −4 |
| Medzibrod | MEDZ_2 | TME_1 | 416.2 | 118.4 | 4 | 28.2 | 393.0 | 111.7 | 369.6 | 119.7 | −5 |
| | MEDZ_1 | TME_2 | | 118.4 | 4 | 28.5 | | 111.7 | | 119.7 | −5 |
| Moldava | MOLD_1 | TMO_1 | 414.2 | 118.6 | 2 | 29.2 | 373.4 | 106.7 | 347.9 | 114.9 | −8 |
| P. Biskupice | PBIS_1 | TPB_1 | 415.3 | 118.4 | 3 | 77.1 | 406.9 | 116.7 | 383.3 | 118.9 | −5 |
| | PBIS_2 | TPB_2 | | 118.5 | 5 | 25.3 | | 115.9 | | 118.6 | 0 |
| R. Sobota | RSOB_1 | TRS_1 | 413.5 | 118.6 | 3 | 24.6 | 376.5 | 108.0 | 347.7 | 116.2 | −8 |
| | RSOB_1 | TRS_2 | | 118.6 | 4 | 23.5 | | 108.0 | | 116.2 | −9 |
| Sp. N. Ves | SNV_1 | TSN_1 | 415.9 | 119.7 | 4 | 49.6 | 381.4 | 109.5 | 357.0 | 118.6 | −9 |
| | SNV_2 | TSN_2 | | 119.6 | 4 | 32.8 | | 109.3 | | 118.2 | −8 |
| Stupava | STUP_1 | TST_1 | 414.2 | 119.7 | 2 | 41.4 | 404.6 | 116.6 | 384.2 | 118.7 | −3 |
| | STUP_2 | TST_2 | | 118.6 | 3 | 27.9 | | 116.1 | | 118.8 | −2 |
| Varín | VARI_A | TVA_1 | 415.7 | 118.9 | 4 | 37.9 | 394.6 | 113.0 | 373.2 | 118.9 | −5 |
| Voľa | VOLA_1 | TVO_1 | 416.6 | 118.7 | 4 | 13.4 | 372.6 | 106.1 | 345.6 | 116.0 | −8 |
| | VOLA_2 | TVO_2 | | 118.4 | 4 | 11.9 | | 105.8 | | 115.6 | −8 |

**Table A3.** Summary data for transformers and voltages in summer: maximum load study.

| TS Node | DS Node | TR | Base Case | | | | Max. Load | | | Max. Load with AVR | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | V1 (kV) | V2 (kV) | Act. Tap | TR Load (%) | V1 (kV) | V2 (kV) | TR Load (%) | V1 (kV) | V2 (kV) | Act. Tap | TR Load (%) |
| Bošáca | BOSA_1 | TBO_1 | 415.0 | 119.0 | 4 | 17.9 | 408.6 | 112.7 | 76.7 | 405.4 | 118.9 | 2 | 56.8 |
| | BOSA_2 | TBO_2 | | 118.0 | 5 | 16.9 | | 113.1 | 55.6 | | 118.1 | 3 | 41 |
| Bystričany | BYST_1 | TBY_1 | 416.2 | 119.0 | 4 | 13.2 | 409.1 | 113.2 | 91.8 | 408.1 | 118.9 | 2 | 64.1 |
| | BYST_2 | TBY_2 | | 119.3 | 3 | 31.1 | | 111.6 | 69.2 | | 118.3 | 2 | 54.4 |
| Gabčíkovo | GABC_1 | TGA_1 | 416.2 | 119.5 | 4 | 33.8 | 415.0 | 113.4 | 127.3 | 414.5 | 119.1 | 4 | 95.7 |
| H. Ždaňa | HZDA_1 | THZ_1 | 413.8 | 118.4 | 1 | 84.7 | 382.5 | 87.3 | 234.2 | 377.5 | 92.6 | −8 | 203.4 |
| | HZDA_3 | THZ_2 | | 118.2 | 6 | 12.1 | | 108.5 | 28 | | 117.1 | 3 | 10.9 |
| Košice | KOSICE2 | TKO_1 | 413.2 | 119.0 | 2 | 34.8 | 396.0 | 111.2 | 94.5 | 391.6 | 117.1 | −2 | 81.7 |
| | KOSICE1 | TKO_2 | | 119.0 | 2 | 34.8 | | 111.2 | 94.5 | | 118.0 | −4 | 81.7 |
| Križovany | KRIZ_1 | TKR_1 | 415.0 | 119.0 | 3 | 26.3 | 410.6 | 114.0 | 88.6 | 408.6 | 118.0 | −4 | 67.2 |
| | KRIZ_2 | TKR_2 | | 119.8 | 3 | 43.4 | | 113.3 | 107.8 | | 118.7 | 2 | 85.7 |
| L. Mara | LMAR_1 | TLM_1 | 418.0 | 118.6 | 4 | 18.5 | 396.4 | 107.4 | 82.3 | 391.4 | 119.6 | −2 | 60.6 |
| | LMAR_1 | TLM_2 | | 118.6 | 4 | 18.3 | | 107.4 | 81.5 | | 119.6 | −2 | 60.1 |
| Lemešany | LEME_1 | TLE_1 | 414.4 | 119.0 | 1 | 17.9 | 398.1 | 111.3 | 57.9 | 393.8 | 118.7 | −3 | 43.9 |
| | LEME_2 | TLE_2 | | 119.1 | 1 | 16.6 | | 112.0 | 46.4 | | 118.9 | −2 | 36.6 |
| Levice | LEVI_1 | TLV_1 | 415.2 | 118.6 | 4 | 14.9 | 407.8 | 113.0 | 71.1 | 405.3 | 118.2 | 2 | 51.7 |
| | LEVI_2 | TLV_2 | | 118.7 | 4 | 16.3 | | 113.5 | 71.3 | | 118.7 | 2 | 52.3 |
| Medzibrod | MEDZ_2 | TME_1 | 418.0 | 119.1 | 4 | 14 | 394.5 | 108.2 | 40.4 | 389.2 | 119.6 | −2 | 31.5 |
| | MEDZ_1 | TME_2 | | 119.1 | 4 | 13.9 | | 108.2 | 40 | | 119.0 | −1 | 31.2 |
| Moldava | MOLD_1 | TMO_1 | 413.7 | 118.8 | 2 | 21.6 | 397.3 | 111.5 | 60.5 | 393.0 | 119.0 | −1 | 46.8 |
| P. Biskupice | PBIS_1 | TPB_1 | 415.3 | 118.5 | 3 | 60.5 | 410.1 | 109.2 | 176.8 | 408.5 | 118.8 | −3 | 140.7 |
| | PBIS_2 | TPB_2 | | 119.2 | 4 | 33.6 | | 112.7 | 114.9 | | 118.9 | 3 | 87.4 |
| R. Sobota | RSOB_1 | TRS_1 | 413.9 | 118.8 | 4 | 8.1 | 403.0 | 113.3 | 35 | 399.2 | 119.1 | 1 | 27.8 |
| | RSOB_1 | TRS_2 | | 118.8 | 3 | 16.7 | | 113.3 | 38.9 | | 119.1 | 0 | 24.9 |
| Sp. N. Ves | SNV_1 | TSN_1 | 416.8 | 118.7 | 5 | 37.6 | 396.8 | 107.7 | 110.1 | 392.1 | 119.3 | −2 | 85.3 |
| | SNV_2 | TSN_2 | | 118.6 | 5 | 20.9 | | 110.2 | 43.3 | | 118.8 | 0 | 36.6 |
| Stupava | STUP_1 | TST_1 | 414.8 | 119.7 | 2 | 27.7 | 408.5 | 113.5 | 77.2 | 407.6 | 118.3 | 2 | 57.9 |
| | STUP_2 | TST_2 | | 119.0 | 3 | 31.2 | | 113.0 | 105.4 | | 118.9 | 2 | 81.1 |
| Varín | VARI_A | TVA_1 | 417.1 | 118.5 | 5 | 42 | 396.6 | 105.7 | 122.9 | 396.2 | 118.5 | −1 | 93 |
| Voľa | VOLA_1 | TVO_1 | 414.8 | 118.5 | 4 | 14.1 | 399.0 | 111.7 | 44.7 | 395.0 | 119.3 | 0 | 34.5 |
| | VOLA_2 | TVO_2 | | 119.4 | 3 | 12.6 | | 112.3 | 50.5 | | 118.6 | 0 | 37.2 |

**Table A4.** Summary data for transformers and voltages in summer: transit study.

| TS Node | DS Node | TR | BASE Case | | | | Max. Transit | | Max. Transit with AVR | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | V1 (kV) | V2 (kV) | Act. Tap | TR Load (%) | V1 (kV) | V2 (kV) | V1 (kV) | V2 (kV) | Act. Tap |
| Bošáca | BOSA_1 | TBO_1 | 415.0 | 119.0 | 4 | 17.9 | 415.0 | 119.1 | 415.0 | 119.1 | 4 |
| | BOSA_2 | TBO_2 | | 118.0 | 5 | 16.9 | | 118.1 | | 118.1 | 5 |
| Bystričany | BYST_1 | TBY_1 | 416.2 | 119.0 | 4 | 13.2 | 415.2 | 118.8 | 415.6 | 118.9 | 4 |
| | BYST_2 | TBY_2 | | 119.3 | 3 | 31.1 | | 118.2 | | 118.6 | 3 |
| Gabčíkovo | GABC_1 | TGA_1 | 416.2 | 119.5 | 4 | 33.8 | 411.2 | 117.9 | 411.1 | 118.3 | 4 |
| H. Ždaňa | HZDA_1 | THZ_1 | 413.8 | 118.4 | 1 | 84.7 | 404.7 | 115.3 | 403.9 | 118.8 | −1 |
| | HZDA_3 | THZ_2 | | 118.2 | 6 | 12.1 | | 116.5 | | 117.2 | 5 |
| Košice | KOSICE2 | TKO_1 | 413.2 | 119.0 | 2 | 34.8 | 385.6 | 110.6 | 381.2 | 117.8 | −4 |
| | KOSICE1 | TKO_2 | | 119.0 | 2 | 34.8 | | 110.6 | | 117.8 | −4 |
| Križovany | KRIZ_1 | TKR_1 | 415.0 | 119.0 | 3 | 26.3 | 414.4 | 118.8 | 414.6 | 118.8 | 3 |
| | KRIZ_2 | TKR_2 | | 119.8 | 3 | 43.4 | | 119.1 | | 118.6 | 4 |
| L. Mara | LMAR_1 | TLM_1 | 418.0 | 118.6 | 4 | 18.5 | 404.8 | 114.8 | 403.4 | 119.4 | 4 |
| | LMAR_1 | TLM_2 | | 118.6 | 4 | 18.3 | | 114.8 | | 119.4 | 4 |
| Lemešany | LEME_1 | TLE_1 | 414.4 | 119.0 | 1 | 17.9 | 388.0 | 111.3 | 383.5 | 118.5 | −4 |
| | LEME_2 | TLE_2 | | 119.1 | 1 | 16.6 | | 111.4 | | 119.5 | −4 |
| Levice | LEVI_1 | TLV_1 | 415.2 | 118.6 | 4 | 14.9 | 405.2 | 115.7 | 403.9 | 119.0 | 2 |
| | LEVI_2 | TLV_2 | | 118.7 | 4 | 16.3 | | 116.1 | | 118.2 | 2 |
| Medzibrod | MEDZ_2 | TME_1 | 418.0 | 119.1 | 4 | 14 | 405.6 | 115.6 | 404.6 | 118.9 | 2 |
| | MEDZ_1 | TME_2 | | 119.1 | 4 | 13.9 | | 115.6 | | 118.9 | 2 |
| Moldava | MOLD_1 | TMO_1 | 413.7 | 118.8 | 2 | 21.6 | 385.8 | 110.8 | 381.4 | 119.4 | −4 |
| P. Biskupice | PBIS_1 | TPB_1 | 415.3 | 118.5 | 3 | 60.5 | 410.8 | 117.3 | 410.9 | 118.3 | 2 |
| | PBIS_2 | TPB_2 | | 119.2 | 4 | 33.6 | | 117.8 | | 118.5 | 4 |
| R. Sobota | RSOB_1 | TRS_1 | 413.9 | 118.8 | 4 | 8.1 | 387.3 | 111.1 | 383.3 | 119.2 | −3 |
| | RSOB_1 | TRS_2 | | 118.8 | 3 | 16.7 | | 111.1 | | 119.2 | −2 |
| Sp. N. Ves | SNV_1 | TSN_1 | 416.8 | 118.7 | 5 | 37.6 | 394.9 | 112.4 | 391.9 | 118.4 | 0 |
| | SNV_2 | TSN_2 | | 118.6 | 5 | 20.9 | | 112.2 | | 119.0 | 0 |
| Stupava | STUP_1 | TST_1 | 414.8 | 119.7 | 2 | 27.7 | 409.2 | 117.9 | 409.2 | 118.6 | 2 |
| | STUP_2 | TST_2 | | 119.0 | 3 | 31.2 | | 117.7 | | 118.8 | 2 |
| Varín | VARI_A | TVA_1 | 417.1 | 118.5 | 5 | 42 | 406.4 | 115.4 | 405.9 | 118.1 | 3 |
| Voľa | VOLA_1 | TVO_1 | 414.8 | 118.5 | 4 | 14.1 | 383.7 | 109.6 | 378.8 | 119.5 | −3 |
| | VOLA_2 | TVO_2 | | 119.4 | 3 | 12.6 | | 110.4 | | 118.7 | −3 |

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