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REVIEWS–LETTERS-REPORTS

The impact of the construction of the new 400 kV transmission power lines between Slovakia and Hungary on the cross-border transmissions

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This article is focused on the analysis of impacts on the cross-border transmissions between Slovakia and Hungary and between Slovakia and Ukraine after the completion of the new 400 kV transmission lines on the cross-border profile Slovakia – Hungary. A simulation model of the Slovak transmission system in software ETAP was created, which is set for exploring the impacts of the new Slovak – Hungarian transmission lines 447, 480 and 481 on the cross-border and national transmissions. Correctness of the created simulation model was confirmed by the match of the measured values from winter nationwide measurement with the calculated values from the simulation model. Subsequently, several variants of the Slovak transmission system operation before and after completion of the new power lines to Hungary were evaluated.

K e y w o r d s: transmission system, power line, unplanned flows, reconfiguration, load flow analysis, ETAP

1 Introduction

Recently, the unplanned power flows of electricity cause major problems in the region of Central East Europe to many transmission system operators in managing and maintaining the operational security of the transmission systems. Unplanned power flows are also the main causes of overloading of overhead transmission power lines. Since August 2011, the situation in the transmission system of the Slovak Republic (TS SR) has been significantly deteriorated due to unplanned power flows, what often results in not reaching the basic safety criterion N-1. The reason is in the big differences between the real and scheduled power flows on the Slovak – foreign transmission profiles, especially on the cross-border profiles Slovakia – Hungary (SK–HU) and Slovakia – Ukraine (SK–UA). The Slovak transmission system operator, company SEPS, has only very limited possibilities for solving the states with increased power flows through the TS SR. Construction of the new 400 kV overhead transmission power lines on the cross-border profile with Hungary presents a conceptual solution needed to avoid overloading of the cross-border power lines on the Slovak – Hungarian and Slovak – Ukrainian profile. This construction will not only result in increase of the transmission capacity and relieve the Slovak – Hungarian cross-border profile, but also relieve the Slovak – Ukrainian cross-border profile, because Ukraine has strong links with Hungary and these two cross-border profiles are closely related [1-4].

2 Current state of the transmission system of the Slovak Republic

Transmission system of the Slovak Republic is synchronously connected with the neighbouring transmission systems except of Austria (AT) in the following ranges [2]:

- one double circuit 400 kV transmission power line to Poland (PL),
- one single circuit 400 kV transmission power line to Ukraine (UA),
- two single circuit 400 kV transmission power lines to Hungary (HU),
- three single circuit 400 kV transmission power lines and two single circuit 220 kV transmission power lines to the Czech Republic (CZ).

The main direction of power flows through the electric power system of the Slovak Republic (EPS SR) is usually from the north or north – west to south and south-east. Large export is from countries with a surplus of electricity generation, which are mostly located in the north, respectively northwest of Slovakia and on the other hand, large import is to Hungary, Ukraine and to the Balkan countries. Slovakia is thus a transit country through which the transmission of large quantity of electricity from the place of its generation to the place of its consumption is realizing [2, 3].

From the comparison of values in Fig. 1 it is visible, that commercial power flows of electricity differ from physical (measured) transmission power flows of electricity, what leads into the creation of unplanned power flows. Unplanned power flows represent any difference between

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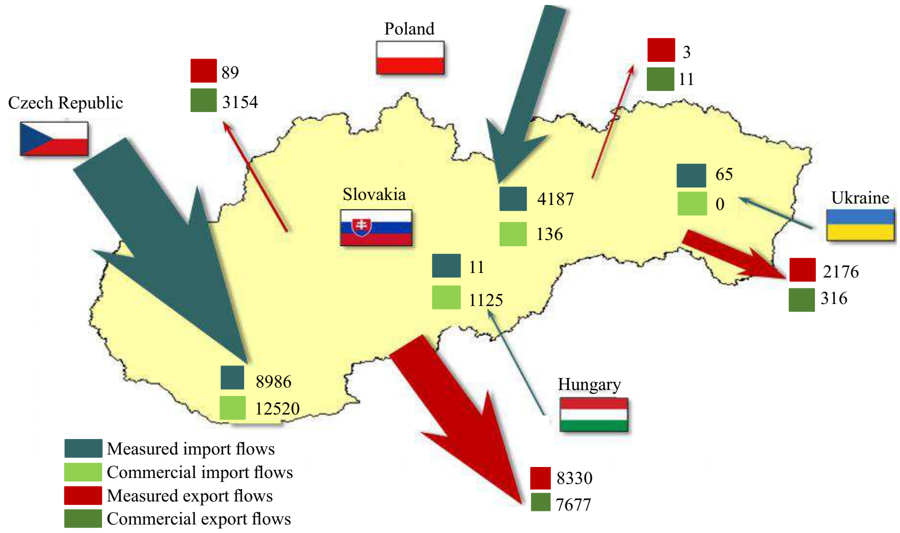

Fig. 1. Commercial and physical cross-border electricity transmissions of the electric power system Slovakia in 2016; Commercial flows: Import – 13787 GWh, Export: – 11159 GWh, Balance: – 2629 GWh, Measured flows: Import – 13249 GWh, Export: – 10 598 GWh, Balance: – 2651 GWh, [2]

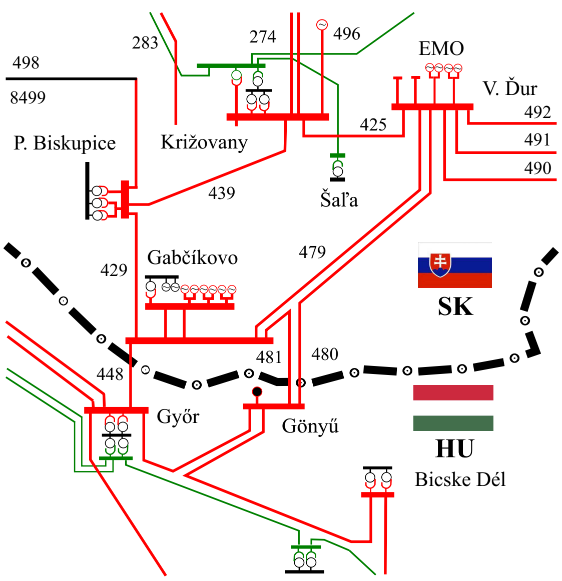

Fig. 2. Schematic interpretation of the new inter – connections with Hungary by the new transmission power lines 480 Veľký Ďur (SK) – Gönyű (HU) and 481 Gabčíkovo (SK) – Gönyu (HU)

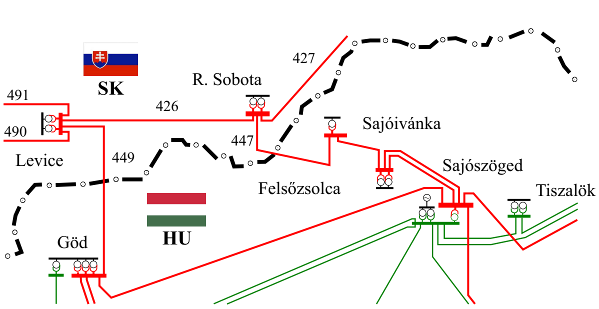

Fig. 3. Schematic interpretation of the new inter – connection with Hungary by the new transmission power line 447 Rimavská Sobota (SK) – Sajóivánka (HU)

the measured physical flows and commercial flows on a given cross-border profile at a given hour, while these unplanned power flows are not taken into account in the cross-border transmission capacity allocation system [3].

Since august 2011, electric power systems of the Slovak Republic, Czech Republic, Hungary and Poland have been persistently exposed to critical situations caused by high unplanned power flows of electricity. The main reasons of unplanned power flows formations are [4 – 7]:

- big export from countries situated in the north from Slovakia and big import to countries situated in the south from Slovakia,
- high production of electricity in renewable energy sources in the areas of the Baltic sea,
- transit of electricity for long distances among production areas and consumption areas through the whole Europe without adequate building of needed transmission infrastructure,
- mutual commercial zone of Germany and Austria,
- insufficient transmission infrastructure for physical electricity transmission within German internal transmission system,
- Germany's decision to shut down all its nuclear power plants by 2022 and replace them by renewable energy sources,
- topology of individual transmission systems.

2.1 Possibilities of power transmission solution on the cross-border profile Slovakia – Hungary

In recent years, transmission system of the Slovak Republic is exposed to increasing transits of electricity, which are most evident on problematic cross-border profiles Slovakia – Hungary and Slovakia – Ukraine.

The Slovak transmission system operator (TSO) has very limited possibilities for solving the situations caused by higher unplanned power flows. Currently, the operational change of topology, so called reconfiguration, is used to limit the unplanned power flows. However, the use of reconfigurations has some disadvantages, therefore the conceptual solution to avoid overloading of cross-border transmission power lines on the Slovak – Hungarian and Slovak – Ukrainian profile is the construction of the new cross-border transmission power lines on the profile with Hungary. These new 400 kV power lines will increase the transmission capacity of the international cross-border profile Slovakia – Hungary and relieve existing inter – national power lines 448 Gabčíkovo (SK) – Győr (HU) and 449 Levice (SK) – Göd (HU) on this profile as well as relieve the inter – national power line 440 Veľké Kapušany (SK) – Mukachevo (UA) on the cross-border profile Slovakia – Ukraine. Specifically, new 400 kV cross-border transmission lines are [8,9]:

- 480 Veľký Ďur (SK) – Gönyű (HU),
- 481 Gabčíkovo (SK) – Gönyű (HU),
- 447 Rimavská Sobota (SK) – Sajóivánka (HU).

Schematic maps of the new inter-connections with Hungary are shown in Fig. 2 and 3.

3 Creation of the simulation model of the transmission system of Slovakia

The ETAP Powerstation software was used for the steady-state simulation and analyses, in a simulation model created according to the actual topology of the TS SR.

3.1 Creation of the simulation model of the TS SR in ETAP Powerstation software

The creation of the TS SR simulation model consists of mutual connections of individual parts of the transmission system. The first step in simulation model creation was modelling of individual electrical substations of the TS SR. Subsequently, these electrical substations were connected by the relevant transmission power lines.

Energy sources were modelled in ETAP software by using blocks called "Generator". In total, six power plants were implemented to the simulation model: hydroelectric power plant Gabčíkovo, pumped – storage hydro power plant Čierny Váh, nuclear power plant Mochovce (block 1, 2 and blocks 3 and 4), nuclear power plant Jaslovské Bohunice (block 3 and 4), steam – gas combined cycle Malženice and thermal power plant Vojany. Each generator was identified by its basic parameters, such as nominal active power and reactive power control range.

When creating a simulation model of the TS SR, it was necessary to select one busbar as a reference one. The reference busbar (block "Power grid" operating in "Swing mode") was situated in the first block of Mochovce nuclear power plant and the voltage value of 415 kV was set on this busbar. The other busbars in the model were designed as loading busbars (MVAr Control) or voltage control busbars (Voltage Control). Active and reactive power are specified on the MVAr Control busbars and the active power and voltage magnitude are specified on the voltage control busbars.

The TS SR model was subsequently interconnected with the neighbouring transmission systems. Electric substations Nošovice (CZ), Sokolnice (CZ), Lískovec (CZ) and Krosno – Iskrzynia (PL) are simplified and contain only feeders with the cross-border power lines leading to Slovakia. A block power grid operating in voltage control mode was implemented in each of these electrical substations. In these blocks, it is possible to set the required voltage value in a given substation and also to set a required value of active power on a corresponding cross-border power line according to the data provided, for example, from a nationwide measurement. However, in a case of such model, the active power on the cross-border power lines between Slovakia and Czech Republic, as well as between Slovakia and Poland after the reconfiguration in the TS SR would remain unchanged. Therefore, it is necessary to manually change the transmitted active power values on these power lines in the case of the reconfiguration in the TS SR. Percentage changes of active powers on individual cross-border power lines with Czech Republic and Poland after the application of the corresponding reconfiguration are defined in SEPS dispatching instruction No. 2/6, [10]. This solution easily allows to set the incoming value of active power from abroad (from the direction of the Czech Republic and Poland) and to monitor changes not only on the cross-border profile Slovakia – Hungary and Slovakia – Ukraine, but also on the national transmission power lines.

The simulation model also includes the northern branch of the Hungarian transmission system connected with the Ukrainian part of the transmission system. Hungarian 400 kV substations Győr, Gönyű, Bicske Dél, Martonvásár, Albertirsa, Göd, Sajószöged, Felsözsolca and Sajóivánka, as well as Ukrainian 400 kV substation Mukachevo were modelled. Hungarian and Ukrainian part of the transmission system was connected by the cross-border power lines with the TS SR. All parameters of generators, transformers, compensative inductors and transmission power lines used in created model of the TS SR were provided by the Slovak TSO – company SEPS.

3.2 Simulation of the winter nationwide measurement in the EPS SR

Model of each real transmission system should be verified by comparing the values obtained by the measurement. Such simulation model can be used as a replacement of the real transmission system only after checking and comparing the matches of the calculated and measured results. Every single year, the summer nationwide measurement in the TS SR is always performed on the third Wednesday of July and the winter nationwide measurement is always performed on the third Wednesday of January. Since the loading of electric power system is the highest in the winter months, the simulation model was compiled for the configuration of the TS SR from the winter nationwide measurement, which was performed on the 18th of January 2017 at 4:00 am, 7:00 am, 10:30 am, 2:00 pm and 5:00 pm. SEPS provided all balance tables of the transmission system, loading diagrams and active and reactive power transfers through transformers in the TS SR for a day of winter nationwide measurement (18th of January 2017). During this day, the TS SR was operating in the basic connection with only one exception – the national power line 051 Hydroelectric Power Plant Gabčíkovo (SK) – switching substation Gabčíkovo (SK) was shut down due to the failure. Simulation model of the TS SR was configured for 5:00 pm, because the active powers on the cross-border power lines to Hungary and Ukraine were the highest at this countdown time. All parameters according to which the TS SR simulation model was configured were provided by SEPS. Subsequently, the compliance between measured and calculated values of active powers and voltages was verified and according to differences, the accuracy of the created simulation model of the TS SR was evaluated.

The highest percentage differences between the measured and calculated value of active power are on the national transmission 400 kV power lines:

- 461 Medzibrod (SK) – Liptovská Mara (SK) (17,1 %, eventually 13 MW),
- 489 Moldava (SK) – Košice (SK) (11 %, eventually 9,7 MW),
- 494 Sučany (SK) – Medzibrod (SK) (11,5 %, eventually 12,1 MW).

The percentage deviation on the 220 kV transmission line 271 Sučany (SK) – Bystričany (SK), reaches a value of 26.7 %, but in terms of active power, the difference between measured and calculated value is only 2.4 MW.

The above – mentioned differences could be caused by the estimated values from the winter nationwide measurement, that were used in the parameterization of the TS SR simulation model, or by the synchronization time during the measurement. The percentage deviations are related to the measured value of active power and reach values up to 10 % on the remaining transmission power lines.

From the above mentioned results follows, that the measured values of active powers through the power lines in the TS SR are approximately the same as the calculated values from the simulation model. From the comparison of measured and calculated voltage values results, that the maximum voltage deviation is ± 4 kV. Following that, the measured and calculated values of voltages in individual substations of the TS SR are in a good conformity and at the same time, the limit values of voltages for voltage level of 220 kV and 400 kV in the simulation calculation were also fulfilled.

As the results of the TS SR operation simulation are approximately the same as the real measured values, it is possible to use this simulation model for further analyses of impacts on the cross-border transmissions between Slovakia and Hungary after completion of the new 400 kV power lines on this cross-border profile.

4 Load flow calculations considering the operation of the new Slovak – Hungarian power lines and various selected states of the TS SR operation

As mentioned above, the most expected projects, which SEPS plans to implement in the following years are the constructions of the new 400 kV transmission power lines to Hungary. The main aim of this article is to determine which impacts will these new power lines have on cross-border transmissions between Slovakia and Hungary, between Slovakia and Ukraine and also evaluate, how the operational situation of other power lines in the TS SR will change, considering various selected states of the transmission system operation. Therefore, three new 400 kV power lines were added to a created and verified simulation model of the TS SR: 447 Rimavská Sobota (SK) – Sajóivánka (HU), 480 Veľký Ďur (SK) – Gönyű (HU) and 481 Gabčíkovo (SK) – Gönyű (HU). The parameters of the new transmission power lines to Hungary entered into the ETAP software were provided by SEPS.

4.1 Variant No. 1 – actual topology configuration of the TS SR (June 2019)

The variant No. 1 is aimed at comparison of the impacts on the cross-border and national transmissions before and after the construction of the new Slovak – Hungarian power lines considering the actual topology configuration of the TS SR (June 2019). Three new 400 kV power lines 447, 480 and 481 to Hungary were added to a created model of winter nationwide measurement and the change of the active power flows in the TS SR was monitored. Parameterization of production and consumption in the EPS SR, transferred active and reactive powers through individual cross-border power lines from the Czech Republic and Poland as well as power balance in a modelled part of the Hungarian and Ukrainian transmission system remained on the same level as during the parameterization of the winter nationwide measurement. After the power flows calculation, the change of the transmitted active power ΔP in MW, its percentage change $\Delta P_{\%}$ and also loading of individual power lines in the TS SR were monitored. Table 1 contains only values for those power lines with occurred significant change of the transmitted active power in comparison with the state without the operation of the new power lines on the cross-border profile Slovakia – Hungary.

Table 1 shows, that the construction of the new power lines 447, 480 and 481 to Hungary will significantly relieve the power line 440 Veľké Kapušany (SK) – Mukachevo (UA). These mentioned changes result in a 156.1 MW decrease of transmitted active power through the power line 440 (decrease of 39.6 % from the initial power value P_{before}), which represents 18.7 % reduction in the power

Table 1. Transmitted active powers and percentage loadings of selected power lines of the TS SR before and after completion of the new Slovak–Hungarian power lines for variant No. 1 (decrease and increase of the transmitted active power/power line load)

Power line	P_{before} (MW)	P_{after} (MW)	ΔP (MW)	$\Delta P_{\%}$ (%)	Power line loading before (%)	Power line loading after (%)	Power line loading change (%)
409	239.2	178.5	-60.7	-25.4	20.9	16.0	-4.9
410	166.8	106.4	-60.4	-36.2	14.5	9.6	-4.9
426	169.1	317.6	148.5	87.8	12.3	22.5	10.2
427	35.7	126.7	91.0	254.9	5.7	12.9	7.2
428	228.7	132.4	-96.3	-42.1	21.4	13.0	-8.4
440	394.5	238.4	-156.1	-39.6	46.3	27.6	-18.7
447	-	309.2	-	-	-	21.6	-
448	506.4	212.7	-293.7	-58.0	35.3	14.8	-20.5
449	696.4	522.2	-174.2	-25.0	48.5	36.5	-12.0
480	86.1	129.6	43.5	50.5	6.5	9.9	3.4
481	-	179.2	-	-	-	12.6	-
487	182.1	217.7	35.6	19.5	17.3	20.7	3.4
488	189.4	220.0	30.6	16.2	17.7	20.5	2.8
489	78.3	108.8	30.5	39.0	10.0	12.9	2.9

line loading. Another significant decrease occurred on the power line 448 Gabčíkovo (SK) – Győr (HU), where the transmitted active power has decreased by 293.7 MW (decrease of 58 % from the initial power value P_{before}), which represents 20.5 % reduction in the power line loading. On the cross-border power line 449 Levice (SK)– Göd (HU), the active power transmission has decreased by 174.2 MW (decrease of 25 % from the initial power value P_{before}), reducing the power line loading by 12 %.

The decreases of the transmitted active powers on each power line by about 60 MW were noticed on the national transmission power lines 409 Lemešany (SK) – Voľa (SK) and 410 Voľa (SK) – Veľké Kapušany (SK), what represent the reduction of the loading of each power line by ≈ 5 %. The decrease of the transmitted active power by 96.3 MW (decrease of 42.1 % from the initial power value P_{before}) has been noticed also on the national power line 428 Moldava (SK) – Veľké Kapušany (SK), thus the power line loading was reduced by 8.4 %.

Relieving the lines 409 and 410 caused a slight increase of the transmitted active power on the national power lines 487 Moldava (SK) – Lemešany (SK), 488 Košice (SK) – Lemešany (SK) and 489 Moldava (SK) – Košice (SK) by about 30-35 MW (increase of each power line loading by ≈ 3 %). On the other hand, more significant increase of the transmitted active power occurred on lines 426 Levice (SK) – Rimavská Sobota (SK) and 427 Rimavská Sobota (SK) – Moldava (SK). Active power on the power line 426 has increased by 148.5 MW (increase of 87.8 % from the initial power value P_{before}), which leads to increase of the power line loading by 10.2 %. On the power line 427, the transmitted active power has increased by 91 MW (increase of 254.9 % from the initial power value P_{before}) and the power line loading increased by 7.2 %. Simultaneously, the direction of the active power transmission through the power line 427 was changed in comparison with the state without new Slovak – Hungarian power lines.

Table 1 also shows the transmitted active powers via new power lines to Hungary. Power line 447 Rimavská Sobota (SK) – Sajóivánka (HU) transmits the active power of 309.2 MW and is loaded at 21.6 %, power line 481 Gabčíkovo (SK) – Gönyű (HU) transmits the active power of 179.2 MW and the power line loading is at the value of 12.6 %. Power line 480 was initially routed from Veľký Ďur (SK) to Gabčíkovo (SK). By changing the route of the power line 480 to Hungarian substation Gönyű (HU), the transmitted active power has increased by 43.5 MW (increase of 50.5 % from the initial power value P_{before}), resulting in the increased power line loading by 3.4 %. After the change of the power line route, the power line 480 Veľký Ďur (SK) – Gönyű (HU) transmits the active power of 129.6 MW and is loaded at the value of 9.9 %. Achieved results are in Fig. 4 and 5.

Active power losses for the explored variant No. 1 and for the state without the operation of the new Slovak – Hungarian power lines reached the value of ≈ 41 MW and after the completion of the new Slovak – Hungarian power lines, active power losses was ≈ 37 MW.

It can be stated, that new power lines to Hungary will help to relieve not only actual power lines 448 and 449 on the Slovak – Hungarian cross-border profile, but also the critical power line 440 on the Slovak – Ukrainian cross-border profile. In this case, there are also no significant changes in the internal topology of the TS SR that would decrease the security of the operation of the TS SR. These new power lines also contribute to increase of overall

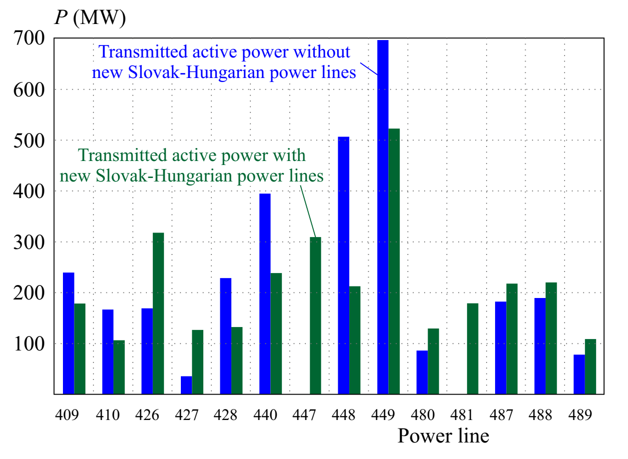

Fig. 4. Transmitted active power via selected power lines of the TS SR before and after completion of the new Slovak – Hungarian power lines for variant No.1

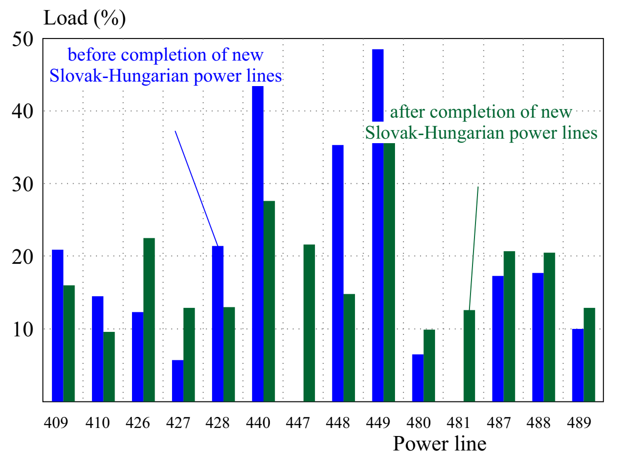

Fig. 5. Percentage loading of selected power lines of the TS SR before and after completion of the new Slovak – Hungarian power lines for variant No.1

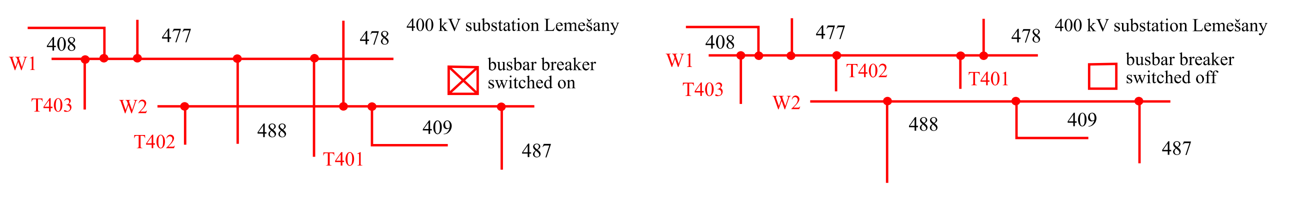

Fig. 6. Basic connection of 400 kv substation lemeany(left), alternate connection of 400 kv substation Lemešany after the reconfiguration(right)

transmission capacity of the Slovak – Hungarian cross-border profile.

4.2 Variant No. 2 – reconfiguration in 400 kV substation Lemešany (SK)

The second variant deals with the changes of the power flows and power lines loadings in the TS SR and on the cross-border profiles Slovakia – Hungary and Slovakia – Ukraine after the reconfiguration in 400 kV substation Lemešany, while the new cross-border power lines to Hungary were included in the simulation model.

The main purpose of the reconfiguration in 400 kV substation Lemešany is the current reduction (decrease of the transmitted active power) on the 400 kV power line 440 Veľké Kapušany (SK) – Mukachevo (UA). Based on the load flow calculations of the TS SR, it was found that due to this reconfiguration it is possible to reduce the loading of the power line 440 by $\approx 30\,\%$ from the value of the transmission in the basic connection of topology, which represents a decrease of the transmitted active power by ≈ 200 MW depending on the conditions in the TS SR. As a result of this topology change, there is an increase of active power flows on the cross-border power lines 448 Gabčíkovo (SK) – Győr (HU) and 449 Levice (SK) – Göd (HU), totalling by about 200 MW depending on the conditions in the TS SR [10].

However, from the previous chapter 4.1 it is visible, that the construction and operation of the new power lines 447, 480 and 481 to Hungary will already relieve the power line 440 by $\approx 20\,\%$ (decrease of the active power by ≈ 155 MW). These values approximately correspond with the values given in the dispatching instruction No. 2/6 [10], which will be achieved after the reconfiguration in 400 kV substation Lemešany considering the actual topology of the TS SR without new Slovak – Hungarian power lines. Construction and further operation of the new cross-border power lines to Hungary could lead into the situation, that for some operational states of the TS SR, it would not be necessary to perform the reconfiguration in 400 kV substation Lemešany as often as nowadays. This will also increase the operational security of the TS SR and eliminate the negative consequences and disadvantages of its using.

Despite of the above-mentioned changes, after the start of the operation of the new power lines to Hungary, it could happen that unplanned power flows through the TS SR will be so high and overloading of the cross-border power line 440 Veľké Kapušany (SK) – Mukachevo (UA) will occur. For this reason, reconfiguration in 400 kV substation Lemešany in ETAP software was simulated, which consisted of dividing the operation in two busbars with a busbar breaker switched off, where the busbar W1 contains feeders of transformers T401, T402, T403 and feeders of power lines 408, 477 and 478, and busbar W2 contains feeders of power lines 409, 487 and 488, Fig. 6.

Parameterization of the simulation model of the TS SR remained the same as during the winter nationwide measurement on the 18th of January 2017 at 5:00 pm.

Table 2. Transmitted active powers and percentage loadings of the inter-national power lines on the cross-border profiles Slovakia – Hungary and Slovakia – Ukraine before and after the reconfiguration in 400 kV substation Lemešany (decrease and increase of the transmitted active power/power line load)

Power line	$P_{\text{before\_rec.}}$ (MW)	$P_{\text{after\_rec.}}$ (MW)	ΔP (MW)	$\Delta P_{\%}$ (%)	Power line loading before reconfig. (%)	Power line loading after reconfig. (%)	Power line loading change (%)
440	238.4	51.5	-186.9	-78.4	27.6	7.9	-19.7
447	309.2	272.6	-36.6	-11.8	21.6	19.1	-2.5
448	212.7	240.2	27.5	12.9	14.8	16.7	2.0
449	522.2	665.5	143.3	27.4	36.5	46.4	10.0
480	129.6	136.3	6.7	5.2	9.9	10.1	0.2
481	179.2	231.0	51.8	28.9	12.6	16.2	3.6

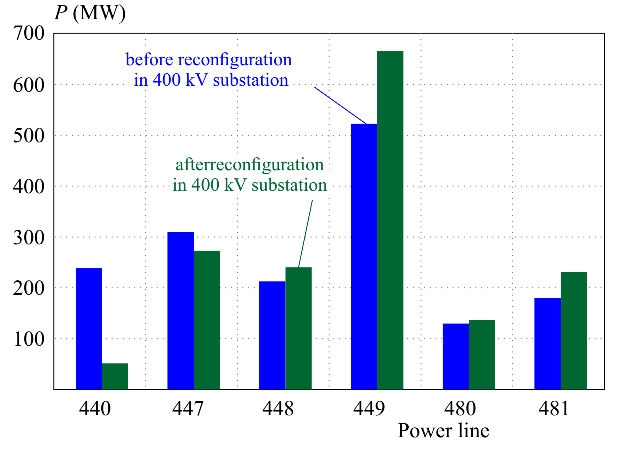

Fig. 7. Transmitted active power via inter-national power lines on the cross-border profiles Slovakia – Hungary and Slovakia – Ukraine before and after the reconfiguration in 400 kV substation Lemešany

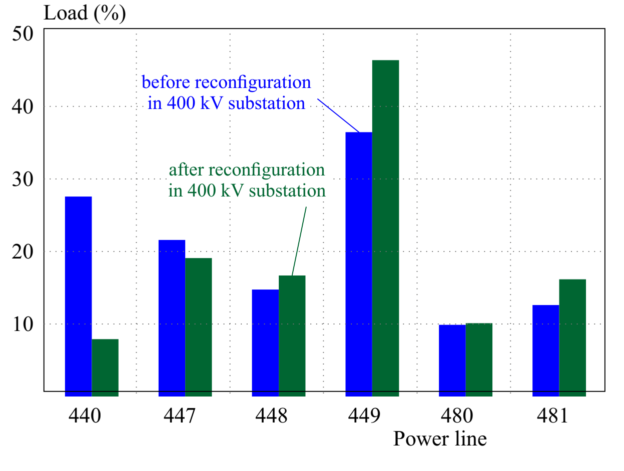

Fig. 8. Percentage loading of the inter-national power lines on the cross-border profiles Slovakia – Hungary and Slovakia – Ukraine before and after the reconfiguration in 400 kV substation Lemešany

During this day, the active power on the power line 440 did not reach the critical value needed for reconfiguration. However, while the new power lines on the cross-border profile Slovakia – Hungary are not in operation yet, the input data for such state were not available (import, export and power balance in the EPS SR). Therefore, the reconfiguration in 400 kV substation Lemešany was simulated for the winter nationwide measurement on the 18th of January 2017 at 5:00 pm taking into account, that the power line 440 was not overloaded. Significant monitored parameters were: the change in the transmitted active power ΔP in MW, the percentage change in the transmitted active power $\Delta P_{\%}$ and the percentage change in the loading of individual power lines of the TS SR. Tab. 2 shows achieved results on the cross-border power lines between Slovakia and Hungary, as well as between Slovakia and Ukraine before and after the reconfiguration in 400 kV substation Lemešany.

Table 2 shows, that the reconfiguration in 400 kV substation Lemešany has decreased the loading of the power line 440 Veľké Kapušany (SK)– Mukachevo (UA) by 19.7 %, which represents the decrease of transmitted active power by 186.9 MW (decrease of 78.4 % from the initial power value $P_{\text{before\_rec}}$). Slight decrease of loading has also occurred on the new power line 447 Rimavská Sobota (SK) – Sajóivánka (HU) by 2.5 %, respectively 36.6 MW (decrease of 11.8 % from the initial power value $P_{\text{before\_rec}}$).

On the other hand, an increase of loading was noticed on the remaining four power lines to Hungary. The biggest changes occurred on the power line 449 Levice (SK) – Göd (HU), where the transmitted active power has increased by 143.3 MW (increase of 27.4 % from the initial power value $P_{\text{before\_rec}}$), which represents 10 % increase of the power line loading. The active power increase on the remaining Slovak – Hungarian power lines was not so significant as on the mentioned power line 449 (Table 2). Active power reduced by the reconfiguration in 400 kV substation Lemešany on the power line 440 and also on the power line 447 will be redirected to the Slovak-Hungarian cross-border profile. The dominant part of the redirected active power is transmitted by the power line 449 to Hungary. Changing the topology of 400 kV substation Levice (SK) would probably relieve the power line 449 and redistribute the redirected power even among the

Table 3. Transmitted active powers and percentage loadings of the selected power lines in the TS SR before and after construction of the new Slovak – Hungarian power lines for variant No. 3)

Power line	P_{before} (MW)	P_{after} (MW)	ΔP (MW)	$\Delta P_{\%}$ (%)	Power line loading before (%)	Power line loading after (%)	Power line loading change (%)
409	246.1	173.3	-72.8	-29.6	21.4	15.6	-5.8
410	173.6	101.2	-72.4	-41.7	15.2	9.1	-6.1
426	266.8	438.7	171.9	64.4	19.1	30.9	11.8
427	132.7	56.0	-76.7	-57.8	12.6	6.7	-5.9
428	251.7	137.5	-114.2	-45.4	23.6	13.5	-10.1
440	424.1	238.4	-185.7	-43.8	50.0	27.7	-22.3
447	-	358.1	-	-	-	25.1	-
448	636.3	252.4	-383.9	-60.3	44.6	17.6	-27.0
449	857.2	646.1	-211.1	-24.6	59.8	45.0	-14.8
480	129.0	185.7	56.7	44.0	9.3	13.4	4.1
481	-	225.1	-	-	-	15.7	-
487	142.4	182.4	40.0	28.1	13.3	17.4	4.1
488	155.3	189.6	34.3	22.1	14.7	17.7	3.0
489	44.2	78.5	34.3	77.6	6.7	10.5	3.7

remaining Slovak – Hungarian power lines. Achieved results can be seen in Fig. 7 and 8.

The TS SR load flow calculations result in fact that after the reconfiguration in 400 kV substation Lemešany, considering the new Slovak – Hungarian power lines, approximately the same parameters will achieved on the power line 440 in comparison with the state after the reconfiguration using actual topology of the TS SR (without considering the new Slovak – Hungarian power lines). This change of topology leads to increase of values of the transmitted active powers on the power lines 448, 449, 480 and 481, overall by ≈ 230 MW.

4.3 Variant No. 3-operation of the new energy sources in the TS SR

The variant No. 3 is aimed at the comparison of the impacts on the cross-border and national transmissions before and after the construction of the new Slovak – Hungarian power lines considering the operation of the new energy sources in the TS SR. Several changes in the composition of the power sources and parameterization of the simulation model of the TS SR have been made. The 3rd block of the nuclear power plant Mochovce with an installed power of 471 MW and the steam-gas combined cycle Malženice with installed power of 436 MW were put into the operation. After the start of the operation of these two power plants, the thermal power plant Nováky was shut down due to the economic reasons (requirement of the SEPS professional staff). The shutdown of this power plant was simulated by increasing the consumption in 220 kV substation Bystričany by about 200 MW. For the same economic reasons, also a one block of the thermal power plant Vojany was decommissioned, which represents the decrease of electricity production in the EPS SR by about 100 MW. For this configuration of the transmission system, the total generated active power in the EPS SR was at the level of 4423.6 MW and the total consumed active power was at the level of 4341.6 MW. It results in fact that the Slovak Republic was self-sufficient in the term of covering the electricity consumption in the country and at the same time, it was possible to export active power from the EPS SR abroad, after the subtraction of the active power losses.

For variant No. 3, import from the Czech Republic and Poland was reduced by 200 MW in total and on the other hand, the consumption in the modelled part of the Hungarian and Ukrainian part of transmission system was increased by 200 MW in total. By this, an increased transit at the level of about 1900 MW through the TS SR to Hungary was simulated. Transit value of 1900 MW via the TS SR is a maximum value according to the document Development program for the period 2019-2028 [3], which can be considered until the construction of the new Slovak – Hungarian power lines. At the transit values higher than 1900 MW, the safety criterion N-1 in the TS SR is not fulfilled. In this variant, the impact of the above-mentioned changes in the TS SR (composition of the new energy sources and increased transit via TS SR) on the cross-border transmissions between Slovakia and Hungary, as well as between Slovakia and Ukraine before and after the construction of the new power lines to Hungary was evaluated. After the power flows calculation, the change of transmitted active power ΔP in MW, its percentage change $\Delta P_{\%}$ and also loading of individual power lines in the TS SR were monitored. Table 3 contains only values for those power lines with occurred significant change of the transmitted active power in comparison with the

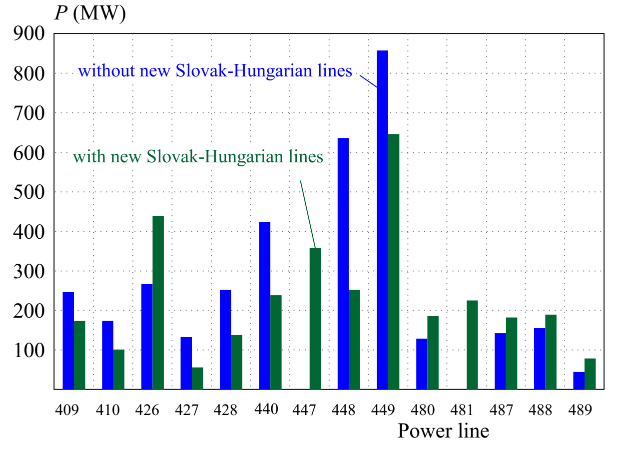

Fig. 9. Transmitted active power via selected power lines of the TS SR before and after completion of the new Slovak – Hungarian power lines for variant no.3

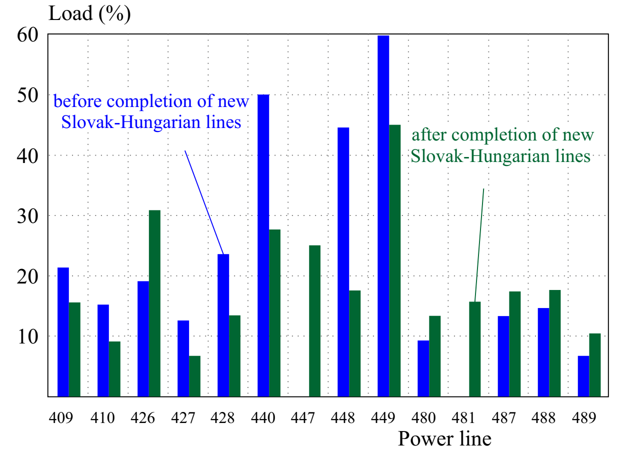

Fig. 10. Percentage loading of the selected power lines of the TS SR before and after completion of the new Slovak – Hungarian power lines for variant no.3

state without the operation of the new power lines on the cross-border profile Slovakia – Hungary.

From the Tab. 3 results, that the construction of the new power lines 447, 480 and 481 to Hungary in a such configuration of the TS SR (the 3rd block of the nuclear power plant Mochovce and steam-gas combined cycle Malženice in operation, thermal power plant Nováky and one block of the Vojany thermal power plant out of operation, transit of 1900 MW via TS SR) significantly relieve the power line 440 Veľké Kapušany (SK) – Mukachevo (UA) by ≈ 185.7 MW (decrease of 43.8 % from the initial power value P_{before}), which represents the decrease in the power line loading by 22.3 %.

The most significant change has occurred on the international power line 448 Gabčíkovo (SK) – Győr (HU), where the active power has decreased by 383.9 MW (decrease of 60.3 % from the initial power value P_{before}), which represents 27 % reduction of the power line loading. The transmitted active power also decreased on the power line 449 Levice (SK) – Göd (HU) by 211.1 MW (decrease of 24.6 % from the initial power value P_{before}), reducing the power line loading by 14.8 %. Based on the calculated values of the active power decreases on the cross-border lines 448 and 449, it can be stated, that new power lines to Hungary will help, in such a configuration of the TS SR, to relieve the actual Slovak – Hungarian power lines. This leads to increasing the operational security of the TS SR. At the same time, new power lines to Hungary will also increase the transmission capacity of the cross-border profile Slovakia – Hungary and after the completion of the 3rd and 4th block of Mochovce nuclear power plant (respectively after the start of operation of steam-gas combined cycle Malženice), it will be possible to securely export the electricity from these power plants abroad.

Table 3 also shows the transmitted active powers via new power lines to Hungary. Power line 447 Rimavská Sobota (SK) – Sajóivánka (HU) transmits the active power of 358.1 MW and is loaded at 25.1 %, power line 481 Gabčíkovo (SK) – Gönyű (HU) transmits the active power of 225.1 MW and the power line loading is at the level of 15.7 %. Power line 480 was originally routed from Veľký Ďur (SK) to Gabčíkovo (SK). By changing the route of the power line 480 to Hungarian substation Gönyű (HU), the transmitted active power has increased by 56.7 MW (increase of 44 % from the initial power value P_{before}), resulting in increase of the power line loading by 4.1 %. After the change of the power line route, power line 480 Veľký Ďur (SK) – Gönyű (HU) transmits the active power of 185.7 MW and is loaded at the level of 13.4 %.

On the national power lines 409 Lemešany (SK) – Voľa (SK) and 410 Voľa (SK) – Veľké Kapušany (SK), a decrease of the transmitted active power on each of the power line by ≈ 73 MW was noticed, which represents a decrease of power line loading by ≈ 6 %. The decrease of the transmitted active power on the national line 428 Moldava (SK) – Veľké Kapušany (SK) by 114.2 MW was also noticed (decrease of 45.4 % from the initial power value P_{before}), what represents the decrease of the power line loading by 10.1 % and also on the national power line 427 Rimavská Sobota (SK) – Moldava (SK) by 76.7 MW (decrease of 57.8 % from the initial power value P_{before}) reducing the power line loading by 5.9 %. At the same time, the direction of the active power transmission through the power line 427 was changed in comparison with the state without new Slovak – Hungarian power lines.

Implementing the mentioned changes resulted in a slight increase of the transmitted active power on the national power lines 487 Moldava (SK) – Lemešany (SK), 488 Košice (SK) – Lemešany (SK) and 489 Moldava (SK)-Košice (SK) by about 35-40 MW (increase of the power line loading by ≈ 4 %). On the other hand, more significant increase of the transmitted active power occurred on the power line 426 Levice (SK) – Rimavská Sobota (SK). Active power on the power line 426 has increased by 171.9 MW (increase of 64.4 % from the initial power value P_{before}), which leads into increase of the power line loading by 11.8 %. Results can be seen in Fig. 9 and 10.

As is visible in Fig. 10 and Tab. 3, with an increased transit of 1900 MW through the TS SR and without the operation of the new Slovak – Hungarian power lines, the power line 440 is loaded at 50 %, 448 at 44.6 % and 449 at 59.8 %. After the construction of the new power lines 447, 480 and 481 to Hungary, the power line 440 will be loaded in the case of this configuration of the TS SR at 27.7 %, 448 at 17.6 % and 449 at 45 %. Therefore, it is obvious, that the construction and operation of the new three power lines to Hungary would significantly relieve the current power lines 448 and 449 on the cross-border profile Slovakia – Hungary and also relieve the power line 440 on the cross-border profile Slovakia – Ukraine.

Active power losses for the variant No. 3 reach the value of ≈ 49 MW in the case of the state within the operation of the new Slovak – Hungarian power lines and after the completion of the new Slovak – Hungarian power lines, active power loses will be ≈ 43 MW.

5 Results

The main aim of this article was to calculate and analyse the influences on the cross-border transmissions between Slovakia and Hungary after the completion of the new 400 kV power lines on this cross-border profile considering the various configurations of the TS SR. In order to be able to examine these impacts, a simulation model of the TS SR had to be created in ETAP software. The accuracy of the created simulation model was verified by comparison of the measured values from winter nationwide measurement from 18th of January 2017 at 5:00 pm and calculated values from ETAP simulation. From the comparison of these values, it can be stated, that created simulation model of the TS SR provides correct results of voltages and active and reactive power flows on the individual power lines of the TS SR. So this simulation model can be further used for analyses of impact on the cross-border and national transmissions after the construction of the new Slovak – Hungarian power lines.

Subsequently, pursuant to the SEPS requirements, three variants of the TS SR operation considering also the operation of the new Slovak - Hungarian power lines, were simulated. As a variant No. 1, the current configuration of the TS SR (June 2019) was chosen, while three new Slovak – Hungarian power lines were implemented in the simulation model. Load flow calculations for variant No. 1 indicated, that the construction of three new power lines to Hungary would relieve the power line 440 Veľké Kapušany (SK) – Mukachevo (UA) by about 20 % and also would relieve the power line 448 Gabčíkovo (SK) – Győr (HU) by about 21 % and 449 Levice (SK) – Göd (HU) by about 12 %.

Variant No. 2 was aimed at the reconfiguration in 400 kV substation Lemešany, while the new power lines to Hungary were implemented into a simulation model. Based on the obtained results, it was found that after the reconfiguration in 400 kV substation Lemešany, considering new Slovak-Hungarian power lines, approximately the same parameters will be achieved on the 440 power line while using the actual connection and topology of the TS SR (without considering new Slovak – Hungarian power lines) – decrease of the power line 440 loading by 20 % and ≈ 190 MW. This change of topology also causes a slight decrease of the power line loading on the new power line 447 by ≈ 3 %. Active power reduced by the reconfiguration in 400 kV substation Lemešany on the power line 440 and also on the power line 447 is redirected to the Slovak – Hungarian cross-border profile. The dominant part of the redirected active power is transmitted to Hungary by the power line 449, where the power line loading has increased by 10 %. There is also a slight increase of the power line loading on the power line 448 by about 2 % and on the 481 about 4 %. There is hardly any change on the power line 480.

It also has to be mentioned, that the construction and operation of the new power lines 447, 480 and 481 to Hungary will relieve the power line 440 by ≈ 20 %. This fact could lead into restriction of using reconfiguration in 400 kV substation Lemešany for some operational states of the TS SR. Restriction of reconfiguration use will cause an increase of the operational safety of the transmission system and will eliminate the negative consequences resulting from its use.

Variant No. 3 presented a modified configuration of the TS SR simulation model. Two new energy sources (the 3rd block of nuclear power plant Mochovce and the steam-gas combined cycle Malženice) were put into the operation. At the same time, increased transit of 1900 MW via TS SR to Hungary was simulated. Load flow calculations for variant No. 3 showed, that the construction of three new power lines to Hungary will relieve the power line 440 Veľké Kapušany (SK) – Mukachevo (UA) by about 22 % and also will relieve the power lines 448 Gabčíkovo (SK) – Győr (HU) by about 27 % and 449 Levice (SK) – Göd (HU) by about 15 %.

Conclusion

The network calculations for all studied variants in this article showed, that the new power lines 447, 480 and 481 to Hungary represent a conceptual solution to relieve and prevent the overloading of existing power lines 448 and 449 on the cross-border profile Slovakia – Hungary and also the power line 440 on the cross-border profile Slovakia – Ukraine. There are no significant changes in the internal transmission system that would decrease the operational security of the TS SR. At the same time, operation of the new power lines to Hungary will increase transmission capacity of the cross-border profile Slovakia – Hungary, so after running the new energy sources in the TS SR into operation, it will be possible to export electricity also abroad. Another benefit of the implementation of the new international power lines to Hungary is the increase of operational security not only of the TS SR, but also of the other transmission systems within the interconnected Europe. All achieved results confirm the validity of the construction and operation of the new cross-border power lines to Hungary.

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