ABSTRACT

The actual and planned capacity of the Slovenian electrical power transmission grid is shown in light of feeding domestic consumers, as well as the huge Italian electrical energy deficit. In parallel with the interconnected grid transmission capacity, its reliability course is shown in order to fulfil the required specifications for the external electric power supply reliability of the Krško Nuclear Power Plant (NPP).

Considering the huge electrical energy production deficit in the vicinity of Slovenia together with its huge transmission grid capacity, the construction of the Krško NPP second unit appears to be very reasonable. The Slovenian economy doesn’t have many other opportunities to increase its gross income and pull the country out of its economic crisis.

INTRODUCTION

Following the construction and commissioning of the 2x380-kV Beričevo-Krško transmission line in the year 2013, a high level of reliability and security of operation in N-1 outages was attained in the Slovenian electric power system (EPS) also in operating states with high power transits towards Italy. Considering the N-1 security criterion, the size of such transits can, in the present transmission grid configuration, reach up to 1500 MW without causing any security of operation violations.

The main bottlenecks for the commercial realisation of major power transits towards Italy are only at the two existing border transmission lines:

- 380-kV DV Divača-Redipuglia, and
- 220-kV DV Divača-Padriciano.

The weak point is primarily the latter, the 220-kV transmission line, which is unable to remain operational in case of outage of the stronger 380-kV transmission line during larger transit flows via the Slovenian transmission grid. This consequently leads to a short, yet unfavourable outage of the entire transit flow at the SI-IT border. A good quality of both interconnection lines towards Italy is that both are equipped with a phase-shifting transformer (PST). The main data and sizes of the PSTs between Slovenia and Italy are:

- 1200 MVA, ±40° in ±32 taps, located at Divača, 380 kV Divača-Redipuglia line,
- 370 MVA, ±31° in 33 taps, located at Padriciano, 220 kV Divača-Padriciano line.

These two PSTs allow us to effectively control power flows within safe limits, since their effect on active power flow control via the SI-IT border is approximately ±800 MW.
Operation-safe limits are determined by the current operating state of the grid, and contribute to the safer operation of the entire Central-Southern region, as the controlled increase of flows towards Italy enables us to disburden the Austrian and Swiss transmission grids.

Although the existing two connections with Italy could be commercially exploited to a greater extent through certain investments, a new SI-IT interconnection would be needed for a more substantial rise in commercial transfer capacities. In this respect, two significant transmission lines are mentioned in development plans, namely:

- the double circuit 380-kV OHL Okroglo-Udine, and
- the HVDC line Beričevo-Salgareda.

Due to hardly surmountable spatial issues and issues involving line siting, the planned construction of the new 380-kV transmission line Okroglo-Udine is stretching into a very indefinite future. For this reason, it would be reasonable to study the possibility of constructing a high voltage direct current (HVDC) cable connection Beričevo-Salgareda with a transfer capacity of at least 1000 MW on the basis of previously implemented technical measures for safe operation of the transmission system in such circumstances. In the transition period up to the target year of construction in 2020, the commercial capacities of the two transmission lines on the SI-IT border could be increased by up to 500 MW (200 MW + 300 MW). This would strongly increase the commercial effects of the SI-IT transit up to the year 2020, and justify the relatively expensive investment in HVDC.

2 DISTRIBUTION OF ELECTRICAL ENERGY PRODUCTION IN EUROPE

Initially, some attention should be devoted to the existing and future states of available surpluses of generation sources, both within the Slovenian electric power zone and in the nearby surroundings. These are, of course, also necessary for the successful technical realisation of major transit flows on the SI-IT border. With insight into the existing and future available electric power generation in the nearby surroundings, we are additionally managing risks related to the economic efficiency of the new interconnection's future operation. This will allow us to evaluate more accurately and realistically the effects of increased social welfare being brought to the entire region by the new investment.

2.1 Actual Electrical Energy Production and Power Flow Transit via the Slovenian Grid

The actual electrical energy production inside the synchronous Continental European Interconnection for the year 3013 [1, 2] is graphically presented in Figure 1. The countries with energy production surpluses are coloured green (the colour intensifies with greater surpluses), while countries with energy production deficits are coloured with red casts.

What is generally obvious from the data presented in Figure 1 is that electrical energy production surpluses exist mainly in the northern part (Germany and the Czech Republic, renewable and thermal sources), and in the western part (France, nuclear sources). On the other hand, the main production deficits are in the central-southern part of Europe, i.e. mainly in Italy, Hungary, Austria, Croatia, Greece, etc. It is obvious that Slovenia is located in the very centre of the countries with huge electricity production deficits. And Slovenia itself is not coloured red due to the simple fact that the energy production of the Croatian part of the Krško NPP is calculated as total Slovenian production.
Figure 1: Distribution of electrical energy production surpluses and deficits inside the European Interconnection for the year 2013 (SI includes NPP Krško’s entire production)

An analysis of past operating states has shown that the levels of unregulated power flows on the SI-IT border in winter have for several years been reaching values well above 1200 MW, at peak times even above 2000 MW. Such conditions are confirmed by the situation in Figure 2, which shows the power flows on the SI-IT border from January 2012 to September 2013. The red line in Figure 2 indicates the calculated flows that would exist on the SI-IT border without limiting or pushing power flow with the help of PSTs on the SI-IT border. Such an actual, unregulated power flow level of around 1200 MW in winter periods exists mainly because of the energy surplus inside the Balkan countries during good hydrological conditions (energy surpluses from Balkan hydro sources).

Figure 2: Power flows on the SI-IT border: the actual flow (blue line), simulated with both PSTs in neutral position (red line), and the commercial NTC level (green line).
The commercial effect of electrical energy transmission from the low market price region (Germany and the Balkans) to the high market price region (Italy) is essential. The Slovenian Transmission System Operator (TSO), ELES, collects up to 10 million € for each 100 MW band of its commercial capacity of power transmission per year at auctions. Due to past mistakes, the actual recognised commercial capacity (NTC) on the SI-IT border is now only up to 730 MW (compared to 1200 MW of average physical power flow and 1500 MW of actual grid capacity). An additional NTC at the most attractive SI-IT border can no longer be achieved without new investments in the transmission grid. As already mentioned, this capacity could rise gradually from the actual 730 MW to 2000 MW with the new final investment – construction of the 1000 MW HVDC Beričevo-Salgareda in the year 2020. The main deficiency of such a Slovenian transmission grid capacity increase lies in the fact that there is no adequate surplus of stable electrical energy production either inside the Slovenian power system or in the closest neighbourhood. For this reason,

- the future transmission grid capacity of neighbouring countries,
- as well as the availability of sufficient energy production surpluses,

are essential in order to achieve the previously mentioned commercial effect of the Slovenian economy.

2.2 Insight into the Future Grid Capacity and New Electrical Energy Sources in Europe

With respect to electrical power transmission via the Slovenian grid to the “export SI-IT border”, the grid capacities of neighbouring countries are also important due to sufficient “import border” capacities. Otherwise, such a huge power transit could lead to increased prices on the internal Slovenian electrical energy market, which is clearly not anticipated. The actual “import border” commercial capacities are limited because of the Austrian power grid transmission bottleneck around Vienna, and the fact that Slovenian grid is still not connected with the Hungarian grid.

On the other hand, the existing energy surpluses of the Balkan countries for export via the Slovenian grid to Italy will be used in future for export via the new 1000 MW HVDC from Montenegro to southern Italy (under construction). The planned increase in power transmission to Italy via the Slovenian grid should be implemented mainly by import from north-eastern energy sources via the Austrian and Hungarian borders. The important future plans for grid strengthening and new power source construction which effect the discussed energy transmission via the Slovenian grid are:

- Construction of a new 380 kV interconnection line Cirkovce-Heviz between Slovenia and Hungary (new “energy import” border for Slovenia, to be completed in 2017). Other additional strengthening of the Hungarian grid for energy transmission in north-south direction is also important.

- Construction of new wind energy sources, i.e. up to an additional 2,100 MW around Vienna in Austria until the year 2017, shall have a very positive effect on the Vienna grid bottleneck and the NTC increase on the A-SI border correspondingly. The Austrian TSO, APG, plans to increase the grid capacity around Vienna with a new 2x380 kV line around this city in future.

- Construction of two new nuclear units in Slovakia in 2015, Mochovce 3 and 4, with a net electric power of 2x440 MW.
A Russian-Hungarian loan agreement was concluded at the beginning of 2014 in connection with the extension of the Paks NPP. The construction of two new units with Russian VVER-1200 reactors is planned in the period from 2015-2023. This new electricity source in Hungary will be hardly sufficient to fulfil the existing Hungarian deficit, but will have a very positive effect on energy transmission to the Slovenian border. However, due to the most recent worsening of relations between the EU and Russia, it will be interesting to observe the future destiny of this project.

Bulgaria recently signed an agreement with Westinghouse for the construction of a new Kozloduy nuclear unit 1000 MW, with planned grid connection in 2022.

However, the best technical solution for the Slovenian Transmission System Operator’s plans to increase electrical energy transmission to Italy is the construction of a second NPP unit in Krško (production increase inside Slovenia is the best technical solution given the fact that all neighbouring countries have huge production deficits).

The construction of the new 1000 MW HVDC line Beričevo-Salgareda will open the “export gate” of the Slovenian grid to the Italian border, with up to 2000 MW in common, while the projects mentioned above will adequately open the “import gates” at the Hungarian and Austrian borders.

3 N-1 SECURITY ANALYSIS AND PROBABILITY OF ELECTRICITY SUPPLY

3.1 Operation Inside Security Limits with HVDC 1000 MW Beričevo-Salgareda

The initial scenario of the 2020a grid with the majority of inflow energy on the border with Austria is shown in Figure 3, [2]. Slovenia’s electricity demand is 1935 MW, which, together with the 1000 MW Beričevo DC demand for Italy, makes for a total demand of 2935 MW. The electricity production inside ELES' transmission grid is 2142 MW. The conventional AC power transit to Italy is 1255 MW. The electricity losses are an indicator of loading conditions in the Slovenian transmission grid and account for 65 MW (normally around 30 MW at lower transits). From a total of 2123 MW of imported power flow, 1029 MW flows into the Slovenia grid via the border with Austria, 407 MW via the Hungarian border and the remainder via the border with Croatia.

In Figure 3 of the grid, the individual numbers alongside the switchyard busbars indicate its voltage in kV, while the pairs of numbers alongside the transmission line, generators and power tapping points indicate MW (upper number) and Mvar (lower number).

The 2020a scenario takes into account the new 2x380-kV transmission line from Cirkovce to the Hungarian border, as well as the new Unit 6 of the Šoštanj Thermal Power Plant (TPP) with an installed generation capacity of 550 MW, which will begin operation in 2015. The current Unit 4 of the Šoštanj TPP with an installed generation capacity of 250 MW will be decommissioned at that time, and so the lack of electricity generation inside Slovenia for the 2020a scenario is more than 2000 MW (imported inflows).

The most critical N-1 outages are analysed, namely:

- outage of the 2x380-kV OHL Beričevo-Krško,
- the 380-kV OHL Beričevo-Divača or 380-kV OHL Melina-Divača,
- outage of the 1000 MW HVDC Beričevo-Salgareda,
- the 380-kV OHL Divača-Redipuglia, and
- outage of the double circuit 380-kV OHL Kainachtal-Maribor.
Figure 3: Initial condition of voltages and power flows inside the 220 kV and 380 kV grid in the 2020a scenario with a total transit power of 2255 MW.

DINSIS Simulation Package
Year 2020a: Initial
The main conclusion of N-1 security analyses is that the implementation of some additional measures inside the Slovenian grid would allow for a total power transit of 1000 MW via HVDC and 1000 MW via existing AC lines without risk or operation security limits violation. And the total power transit can be strictly controlled by existing PSTs and HVDC.

The second conclusion is connected with additional power generation units inside the Slovenian grid. Considering the huge electrical energy production deficit in the vicinity of Slovenia, together with its huge transmission grid capacity, the foreseen construction of a second Krško NPP unit seems very reasonable.

3.2 Actual Probability of External Electricity Supply from the Krško NPP

The probability of electricity supply for a past period can be calculated via statistical data collection of the sufficiency (s) or insufficiency (p) of each particular element comprising the entire supply for the appointed source point. The relation between those terms is simply

\[ p = 1 - s \]  \quad (1)

The common insufficiency of two serial supply elements is the sum of both elements’ insufficiencies, while the common insufficiency of two parallel elements is the product of both values. A probability calculation of external AC supply from the Krško NPP was made in 1993 [3] by the Milan Vidmar Electric Power Research Institute on the basis of statistical data on the insufficiencies of supply. On the basis of that data, the past time insufficiency of supply from the 380-kV Krško grid point is determined as

0.17 hours/year, which means \( p_{380\text{kV}} = 2 \cdot 10^{-5} \),

while the insufficiency of supply from the 110-kV Krško grid point is calculated as

7.3 hours/year, which means \( p_{110\text{kV}} = 8.36 \cdot 10^{-4} \).

Statistical data for the period from 1980 to 1992 noted quite frequent electrical system collapses with no voltage at the Krško supply point (approx. one event every 5 years, giving 0.17 hours per year of no electricity supply). The FSAR [4] of the Krško NPP estimates one event or one system collapse within a period of 20 years, but does not determine the non-supply in hours. We can conclude that the actual frequency of system collapse during that past period was considerably higher, but with no serious events regarding no supply time duration.

What can we say or predict in connection with the actual probability of external electricity supply from the Krško NPP? It is true that the frequency of present-day events is significantly smaller. And if there is no consecutive statistical data, then it is not possible to calculate the adequate probability of supply. In the years of the new millennium, there have been no events with any external voltage supply at the Krško grid point. It is also shown above that the actual Slovenian grid is very strong and very secure on N-1 outages.

However, we cannot say that nowadays the probability of external supply from the Krško NPP is essentially different or higher than at the time of [3]. This is true; the outage of a particular line doesn’t mean anything in terms of security and probability of supply. For example, even all 380 kV line outages at the Krško switchyard do not lead to the collapse of supply via 110 kV lines. On the other hand, the Slovenian electric power system is tightly interconnected with the Continental European Interconnection (former UCTE). During any possible severe incidents inside this huge electrical interconnection, there is the possibility of total system collapse or total non-supply of electrical energy from the Krško grid point. And the duration of such a total system collapse could be significantly longer.
In the first decade of the new millennium, there were two serious incidents inside the UCTE interconnection, which confirms the final statement of this chapter. The first was a total Italian electricity system collapse [5] in 2003. The lesson learned from this event was that the restitution of electricity supply after such an extensive event can even last several days. The second event, which occurred in 2006, shows that even a simple, single outage in such a huge interconnection under heavily loaded conditions can lead to total system collapse. Such total collapse of supply did not occur during that event [6], but we were not far away from it.

The same unfavourable reasons for the decreasing stability and security of electricity supply inside the European Interconnection, namely, the greed of the market environment and the expansion of uncontrolled renewable sources, still exist today. Even more, they are on the increase. This means that we cannot say that the insufficiency of external electricity supply from the Krško NPP is lower than that calculated in [3]. It is approximately on the same level, with a lower frequency of events, but with a higher time duration (more serious consequences of a rare event).

4 CONCLUSION

The Slovenian transmission grid is strong and ready to take over not only the domestic supply, but also a significant amount of electrical energy transmission from the European region with low market prices to the high market price region. For this reason, energy transfer is quite a profitable business, just as it is profitable to ensure the reasonable production of electrical energy in the vicinity of high market price regions. Slovenia is located in the middle of a European region with a huge lack of electricity production, and its opportunity for constructing a second unit of the Krško NPP is evident.

In spite of a very strong transmission grid with no local problems in electricity supply, the probability of external electrical supply of the Krško NPP is not increasing. The possibility of the whole European Interconnection collapse is increasing due to huge market-oriented energy transfers, as well as enormous amounts of uncontrolled renewable sources. The restoration of electricity supply after such a rare event could be very time consuming.

REFERENCES