The Impact of JEK2 on the Operation of the Slovenian Electrical Power System

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ABSTRACT

Slovenia is deciding on the direction of the future energy development. The latest international commitments accepted by EU and adopted by Slovenia dictate an increase in electrical energy production from clean low-carbon sources without CO2 emissions and an abandonment of fossil energy sources as a basis for the transition to a low-carbon society. A very reasonable solution to facilitate such transition is the further development of electrical energy production capabilities from nuclear power plants (NPP). In that respect construction of a new nuclear power plant JEK2, with installed capacity of about 1100 MWe, is proposed.

The impact of the new NPP JEK2 on the operation of the Slovenian electrical power system mainly depends on the state of the system generation, consumption, network topology and transit power flows between the adjacent ENTSO-E members. A study of the electrical power system operation from a stationary and dynamic point of view with JEK2 being constructed and connected in 2030 has been performed. The stationary N-1 and N-1-1 security analysis, which also includes generation unit tripping and bus tripping, identifies the most critical network operating conditions and the related critical network infrastructure from a stationary aspect. The dynamic analysis then takes the identified most critical conditions as an input and analyses the impact of failure of individual network infrastructure (trips of main production units and critical failures in transmission system) from a dynamic aspect. Dynamic analysis mainly focuses on the angle and voltage stability in the Slovenian electrical power system. Moreover, a transient stability and critical clearing time analysis of the new NPP JEK2 is presented.

The study includes two scenarios. The first one depicts the state of electrical power system in 2030, when the main generation units in Slovenia (NEK 703 MWe, TEŠ6 542 MWe and JEK2 1100 MWe) could be in operation. The second one shows the state in 2043 with NEK and TEŠ6 being shut down. Planned transmission system upgrades and new or improved connections to neighbouring countries are also considered. Along the proposed installed capacity of 1100 MWe, also the maximum acceptable capacity is estimated for secure and stable electrical power system operation.

The results of the study show that the connection of JEK2 unit to the Slovenian electricity network is feasible. Moreover, the new unit along to its substantial low-carbon energy production will significantly contribute to the stability and reliability of the Slovenian electrical power system. The new NPP JEK2 will crucially increase the power system inertia and thus improve its electromechanical

disturbance immunity. Consequently, the NPP with traditional reliability and inertia will be essential for development of the unpredictable renewable power sources.

1 INTRODUCTION

This paper analyses the operational feasibility and the possibilities of connecting a new nuclear power plant (NPP) JEK2 to the electrical power system of the Republic of Slovenia. For such analysis, a simulation model of the Slovenian electrical power system along with a wider area of electrical power systems in ENTSO-E has been built. The initial state of the network is set in 2030, when a connection of JEK2 with a nominal net electric power of approximately 1100 MW is planned. The new unit JEK2 is expected to operate in parallel with the existing 703 MW NPP called NEK for at least another 10 years until the NEK closure, which is planned for 2043. Therefore, an additional analysis of the JEK2 connection impact for 2043 has been made. The latest energy baselines are considered, which include forecasts of the current:

- National Energy and Climate Plan of the Republic of Slovenia [1],
- Development Plans of the Transmission Network of the Republic of Slovenia 2019-2028 & 2021-2030 [2] and
- Ten-Year Network Development Plan of the European Network of Transmission System Operators for Electricity (ENTSO-E TYNDP 2020), which in its most realistic Global Ambition (GA) Scenario envisages the construction of JEK2 [3]–[5].

These include: the forecasts of the peak and minimum electrical power demand, the planned development of the electrical power capacities, electricity generator engagement and the transmission system, as well as the forecasts of the worst-case cross-border flows through the power system of the Republic of Slovenia.

The core of the study are the stationary and dynamic analyses. Stationary analyses include an analysis of the worst-case power flows that are present in the most critical state of the network without any element failure, a sensitivity analysis that includes the impact of the electricity demand variation, cross-border flow variation and distributed energy resources engagement and finally, a contingency analysis (N-1, N-2, etc.) of the worst-case initial states. Dynamic analyses include the analysis of electromechanical transients (voltage and angular conditions in the event of power outages and network transient stability).

This paper is based on the detailed analyses given in [6].

2 STATIONARY ANALYSIS

In stationary analysis, JEK2 with nominal net electrical power of 1100 MW is connected in parallel to NEK (the existing NPP). Part of the visual presentation of the simulation model is given in the following Figure 1.

The scenario analysis is structurally shown in Figure 2. After setting the consumption and engaging resources for the design of daily or night scenarios, we shape a sensitivity analysis with the variants described in Figure 2.

The process is automated in the background of the simulation tool. In doing so, we observe which of the variants are the most unfavourable in a stationery manner. In the event of line overloads or voltage breakdowns, we can act in a few different ways that are possible in the simulation environment. By priority, such measures are:

- resetting of the PST on the Italian-Slovenian border
- resetting the operating point of modern devices (FACTS, BESS, HVDC)
- resetting of the operation point of HVDC,
- redispatching of the generation units
- infrastructure measures such as building new or upgrading the existing connections.

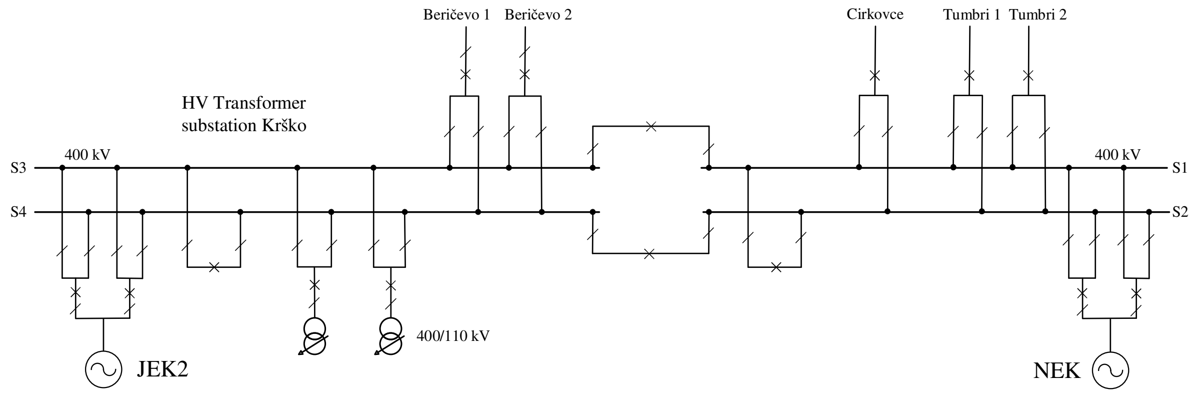

Figure 1: Scheme of JEK2 connection in the HV transformer substation Krško

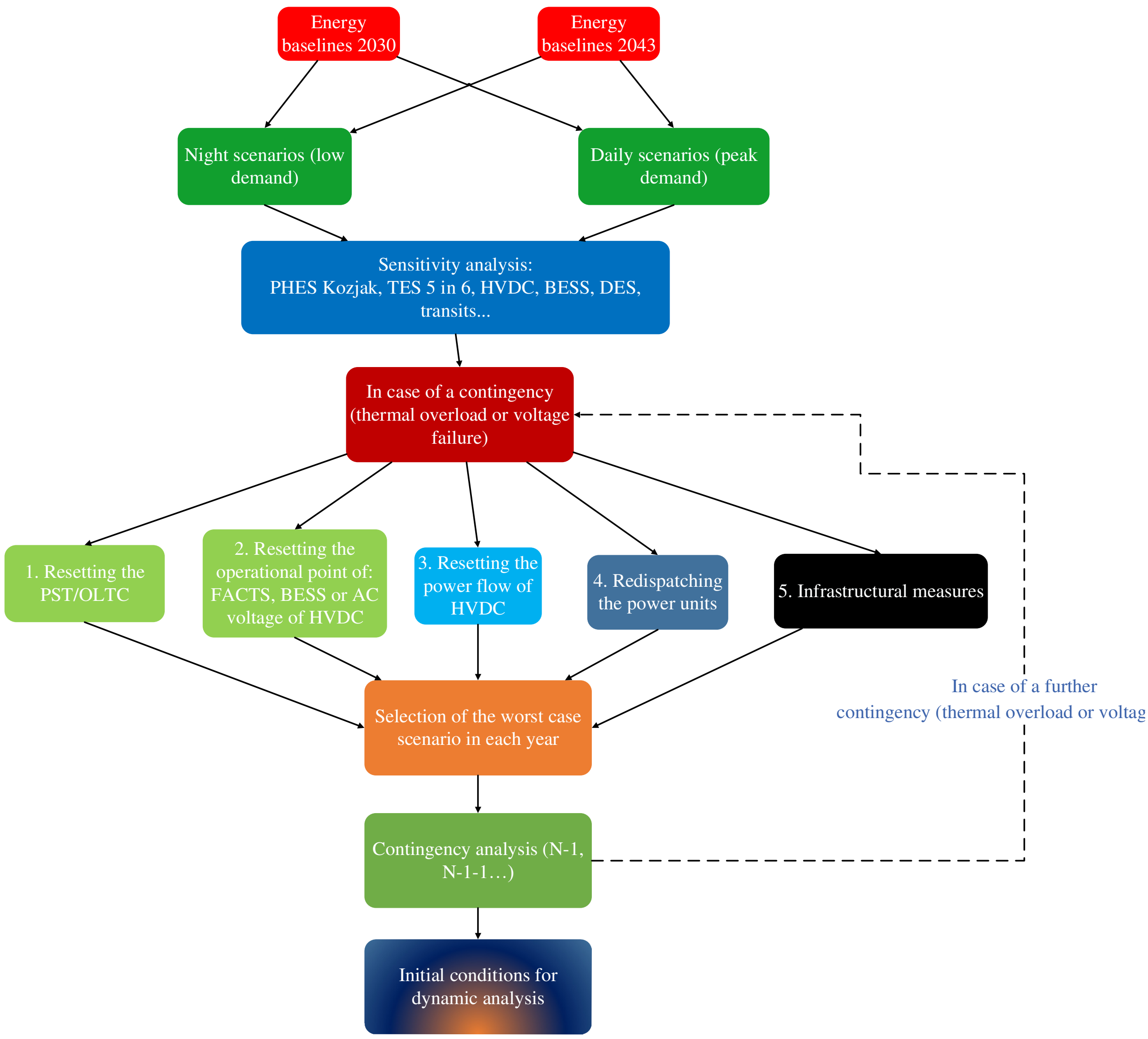

Figure 2: Schematic diagram of stationary analyses

We try to avoid redispatching and infrastructural measures if a congestion can be eliminated by using the first three measures. In 2030 and 2043, we selected the worst-case stationery scenarios by further performing of detailed contingency analysis with the following types of outages:

- A failure (symmetric 3-phase tripping) of one single connection (*N* -1), either a line or a transformer at 400, 220 or 110 kV level in the Slovenian power system along with interconnections,
- A tripping of the largest generation unit connected to each 400, 220 or 110 kV busbar in the Slovenian power system,
- A simultaneous (*N* -2) or consecutive (*N-1-1*) failure of two connections connected to the same 400, 220 or 110 kV bus in the Slovenian power system (e.g., Beričevo 400 kV - Divača 400 kV and Beričevo 400 kV - Podlog 400 kV) and
- A simultaneous failure of parallel (double) connections (*N -2*), on one bus in the Slovenian power system together with interconnection connections (e.g., simultaneous failure of double connection Krško 400 kV -Beričevo 400 kV or simultaneous failure of two connection Krško 400 kV -Tumbri 400 kV, etc.)
- A failure of each busbar at the 400, 220 or 110 kV level in the Slovenian power system.

2.1 The representative power system state in 2030

NEK and JEK2 operate in parallel with maximum power. TEŠ6 operates at maximum power, while TEŠ5 is at standstill. PHES (Pump Hydro Energy Storage) Avče is also operating at full power in generator mode (180 MW). The total power generation in Slovenia is 3654.5 MW, and the measured at the HV/MV transformers considering the generation of DES is 2220.0 MW. The largest physical flow is directed toward Italy, namely 1313.8 MW. There is no Slovenian-Italian HVDC nor PHES Kozjak operating in the power system. The Ravne 220 kV interconnection between Slovenia and Austria, and the Cirkovce-Pince-Heviz 400 kV interconnection between Slovenia and Hungary are built and operating. The system is stable, without overloads and voltage failures. Voltages are within their limits and the 400 kV and 220 kV connections are below their thermal limit.

2.2 The representative power system state in 2043

NEK is no longer in operation, and JEK2 is operating at maximum power. TEŠ6 and TEŠ5 are no longer operating. PHES Avče is also operating at full power in generator mode (180 MW). In contrast to 2030, the total power generation in Slovenia in this scenario is consequently lower and equals 2319.5 MW. The demand measured at the HV/MV transformers considering the production of DES is higher and equals 2700.0 MW. We have the largest physical flow towards Italy, namely 1255.5 MW. There is no Slovenian-Italian HVDC nor PHES Kozjak operating in the power system. The Ravne 220 kV interconnection between Slovenia and Austria, and the Cirkovce-Pince-Heviz 400 kV interconnection between Slovenia and Hungary are built and operating. The system is stable, without overloads and voltage failures. Voltages are within their limits and the 400 kV and 220 kV connections are below their thermal limit.

2.3 Load flow results

The Slovenian-Italian border already represents the weakest spot in the Slovenian power system and is very sensitive to variations in transit with neighbouring countries. In fact, it was observed than even ± 200 MW variations in consumption do not have as great impact on the power system as variations in transits, especially on the Slovenian-Italian border. At the Slovenian-Italian border, there are also higher physical flows that exceed the indicative NTC (Net Transfer Capacity) values by 20-30%. Already in the normal conditions, coordinated angle adjustments of the Slovenian PST Slovenian pair (Divača 400 kV - Redipuglia 400 kV, 2x600 MVA) and the Italian PST (Divača 220 kV - Padriciano 220 kV, currently 365 MVA) are necessary. However, there are no problems with voltages, neither in the night nor in the daily scenarios. Krško substation maintains its voltage in the interval 1-1.02 pu (100% -102%). Upgrade of the Divača-Padriciano PST (from 365 MW to 680 MW of thermal capacity) is in any case highly desirable.

JEK2 1100 MW does not represent a cause of thermal overload in the system. The power system is strong, the interconnection lines are underloaded and ready to increase cross-border flows even after the inclusion of the JEK2 1100 MW unit. JEK2 would only further contribute to voltage regulation due to its reactive power capability adjustments, which is expected from one major new modern electricity production unit. This would make the Slovenian power system even more powerful in providing reactive power and thus stabilizing the voltage in the power system.

2.4 Congestion analysis

1665 different combinations of outages were simulated in the manner described in the previous subchapter (N -1, N -1-1, N -2, parallel lines etc.). If a certain connection is thermally overloaded above 100% of its thermal limit, we say that there is a congestion. The analysis shows that the highest overloads occur in the failure of elements related to the Divača substation. The results of the analysis are taken from the simulation environment of Siemens PSS-E v35.1 contingency analysis module.

In 2030, we identified 15 overloads. The share of violations (exceeding) 100% of the thermal limit of connections is 15/1665. This means that in 100% -0,9% = 99,09% of all combinations of outages, there was no overload without additional congestion management measures, which is an exceptional number. In 2030 the upgrade of the Italian PST Padriciano – Divaca is already included, from 365 MW to 680 MW of thermal capacity at normal operating temperature.

In 2043, we identified 11 congestions. The share of violations (exceeding) of 100% of the thermal limit of connections is 11/1665. This means that in 100% -0,67% = 99,33% of all combinations of outages, there was no overload without additional contingency management measures, which is again an exceptional number.

All overloads in 2030 and 2043 were eliminated by appropriate adjustment of the PST angle (in substation Divača; 400 kV and/or 220 kV), or by resetting or activating FACTS devices. The stationary analyses have shown that the connection of JEK2 with a nominal net active power of 1100 MW in the Slovenian power system is feasible.

3 DYNAMIC ANALYSIS

The simulations were created using the simulation module for dynamics from the Siemens PSS-E software package [7]. The model includes a network of more than 200 nodes as well as over 200 power plants. For JEK2 and other future generation units, we used the best possible generic RMS (root mean square) models for generators, excitation systems and turbine governors from the collection of IEEE models or the collection of dynamic models PSS®E [8]. As adequate accurate data on JEK2 could not yet be obtained, standard data for modern NPPs was assumed. The basic parameters of the JEK2 synchronous generator and JEK2 step-up transformer are provided in the following tables (Table 1 and Table 2, respectively).

Table 1: Description of parameters of JEK2 1100 MW synchronous generator

JEK 2 synchronous generator, 1100 MW, Revision 2020			
Parameter description	***Label***	***Unit***	***Value***
Nominal apparent power	S_n	MVA	1278
Gross electrical active power	P_{ng}	MW	1150
Net electrical active power	P_n	MW	1100
Nominal generator terminal voltage	U_n	kV	21
Number of pole pairs	p	-	2
Nominal synchronous mechanical rotor speed	n	min^{-1}	1500
Machine inertia constant (=W_k/S_n)	H	s or MJ/MVA	3,7

Table 2: Parameters of the 3x500 MVA parallel connected generator step-up transformers

JEK 2 generator step-up transformers, Revision 2020			
Parameter description	***Label***	***Unit***	***Value***
Nominal apparent power of the transformers	S_n	MVA	1500
Nominal active power	P_n	MW	1300
Percentage impedance	u_k	%	12/3
Primary/Secondary transformer winding voltage	U_{prim}/U_{sek}	kV/kV	21/400

In this chapter we give a critical assessment of system stability due to JEK2 connection in the Slovenian power system. The analysis provided below in only an approximation of the real behavior of the power system, especially in 2043, since we do not have precise JEK2 data, and at the same time we do not know how the future distributed energy sources and power electronics converters will behave considering the system stability.

3.1 JEK2 tripping in 2030

The first condition for the secure connection of JEK2 in the light of dynamic analysis is the impact of JEK2 outage on the rest of the Slovenian power system. Only a part of the time courses is shown in Figure 3-6. The courses themselves show that the transient, frequency and voltage stability is maintained. The maximum frequency deviation is only 100 mHz. Bus voltages fluctuate with a maximum 2% deviation from the initial state; they remain within tolerance limits until the end of the transients. The rotor angles show oscillations that slowly fade and stabilize after 40 s. Speed variations are negligibly small below 0.1%.

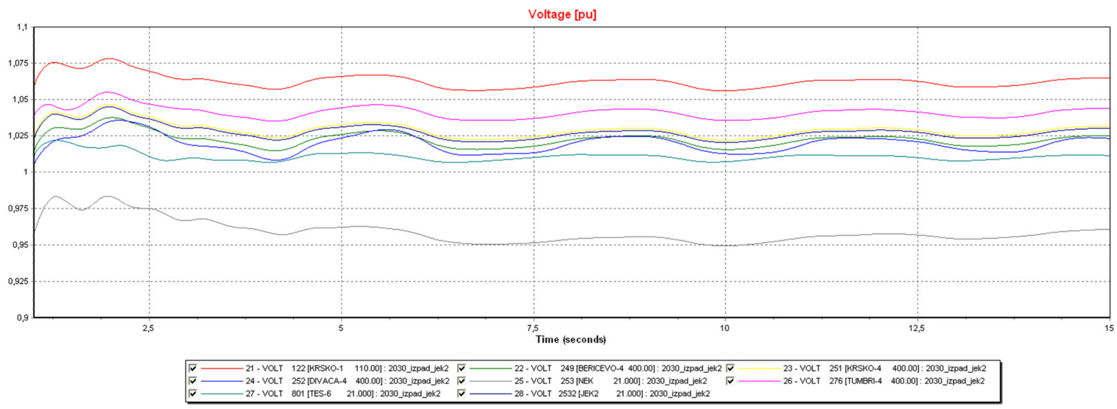

Figure 3: Bus voltages in the Slovenian power after the tripping of JEK2 in 2030

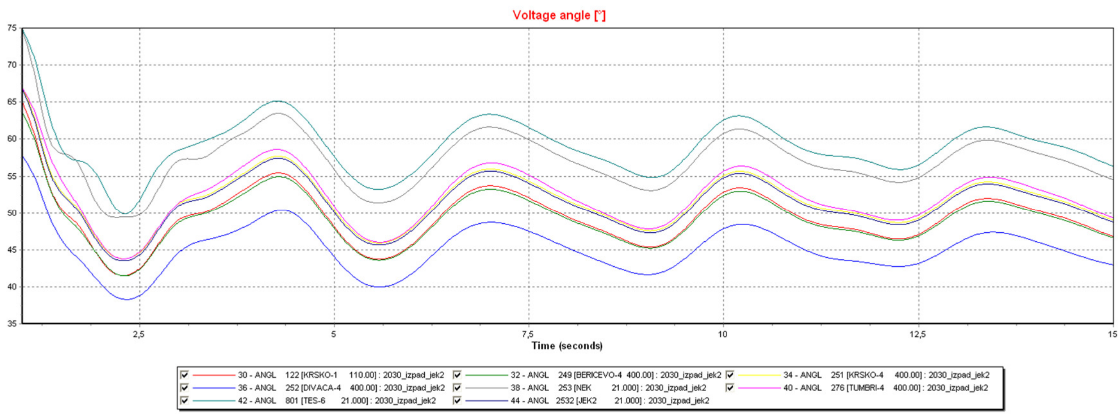

Figure 4: Voltage angles in the Slovenian power system after the tripping of JEK2 in 2030

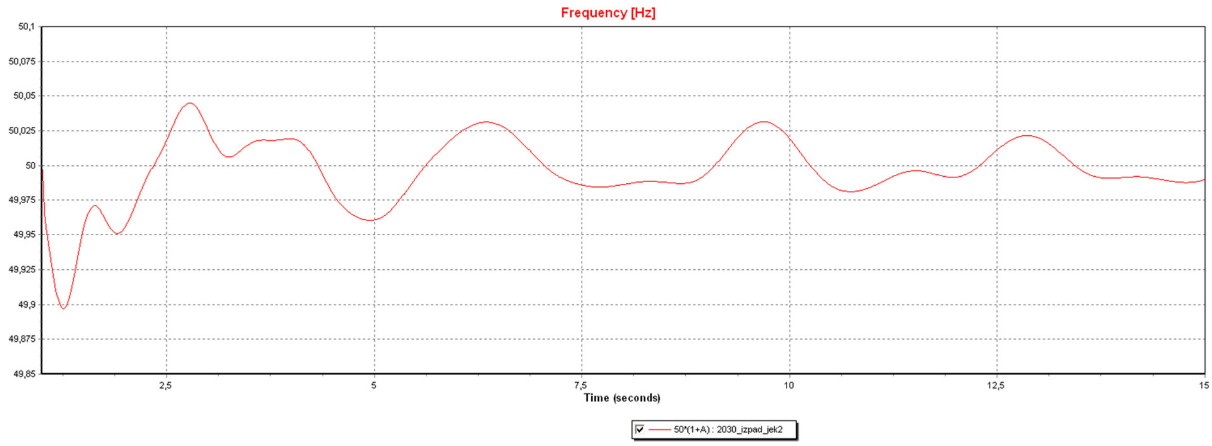

Figure 5: Frequency in Slovenian power system after the tripping of JEK2 in 2030

Figure 6: Relative rotor speed deviation in the Slovenian power system (NEK – red, TEŠ6 – green) after the tripping of JEK2 in 2030

3.2 NEK tripping in 2030

Also, in this case, we observed a transient stable behavior of the system with a tolerant presence of fluctuations in quantities, which is expected in the event of such a failure. Frequency and voltages are kept within the dynamic limits. The maximum frequency deviation this time is only 60 mHz. Voltages do not deviate by more than 1% of their initial value. The transient phenomenon disappears in less than 10 s. The deviation of the rotational speed at the same units this time does not exceed even 0.03% of the initial value.

3.3 JEK2 tripping in 2043

We analyse the impact of the instant failure of JEK2 1100 MW, which according to the predicted energy scenarios would be the only classic electricity production unit connected to Krško and the only major source of classical inertia in the system. TEŠ6 and NEK are no longer operating in this scenario. The failure of a synchronous generator with a rated power of 1100 MW causes such a situation in the system that Krško substation is left without the support of a synchronous generator. The frequency deviation is again only 60 mHz. Bus voltages increase up to 2%. The system remains stable even after such a failure. This is an indicator that the Slovenian power system is strongly involved in the ENTSO-E network in 2043. The location of the Slovenian power system in the ENTSO-E network is very favourable from the point of view of dynamic phenomena.

3.4 JEK2 critical clearing time in 2030 and 2043

We observed the rotor angle of NEK, JEK2 and TEŠ6 at the occurrence of a three-pole short circuit in Krško HV substation. We found that the phenomenon is transiently stable during the short circuit duration of 200 ms in 2030 and 220 ms in 2043. In any case, we must emphasize that the new critical clearing time is significantly longer than the response time of the bus differential protection, which ranges between 50 ms - 100 ms, which means that the connection of JEK2 to the Krško substation is secure.

For the secure operation of production units connected to Krško substation (NEK, JEK2), regardless of the year of connection (2030 or 2043), we found based on simulations that the reaction time of 1. zone of distance protection (80-85% of the length of the line connected to the Krško substation) should not exceed 200 ms. Such operation is already guaranteed nowadays since the relay reaction time could be calibrated to 150 ms. Reaction time of the 2. zone of distance protection is desirable to be set in the interval 200-250 ms. It is highly recommended to use differential protection or distance protection with the transfer of criteria around JEK2.

3.5 Estimation of the JEK2 maximal nominal electrical power

Repetitive iterations of the stationery and dynamic analyses were made by increasing the nominal net electrical power of JEK2. It was showed that the connection of JEK2 2x1100 MW variant is feasible and secure for the power system, both in 2030, as well as in 2043. The maximum estimated threshold of JEK2 nominal net electrical power in the implementation of one individual unit is approximately 2000 MW in 2030 or 2200 MW in 2043. As a result, an increase in the nominal net electric power of JEK2 1x1100 MW by more than a few hundred megawatts, both in 2030 and in 2043, is certainly permissible - it does not cause instability in the operation of other units in the Slovenian power system and is acceptable from the point of view of the power system protection.

4 CONCLUSIONS

Reliable and high-quality electricity supply is conditioned by the operation of tested stable electricity production units. One of the most reliable and environmentally friendly sources with zero CO2 production of electricity is a new nuclear unit JEK2. Slovenia would need such capacity of stable zero carbon production unit as soon as possible, otherwise in next 10 to 20 years the electricity self-sufficiency will become questionable for the country. Without it, the ambition for electricity self-sufficiency of the Slovenian power system will become questionable in the next 10 to 20 years.

The simulations were created using adequate simulation modules for stationery and dynamics analysis from the Siemens PSS-E software package. The model includes a network of more than 200 nodes as well as over 200 power plants across the ENTSO-E network. In 2030 and 2043, according to the newest energy baselines, the initial worst-case stationery conditions were found by doing a deliberate sensitivity analysis of different power source dispatch and modern device configurations in the power system. Stationary analysis has shown that the connection of JEK2 with a nominal power of 1100 MW in the Slovenian power system in 2030 and 2043 is completely feasible. The established extremely small number of thermal overloads (less than 1%) can be eliminated with simple operational interventions even in the most critical stationary state of the Slovenian power system, such as appropriate adjustment of the PSTs angle, or by resetting or activating FACTS devices. No contingency was found that could not be eliminated. No voltage failures were found exceeding the 5% tolerance. The connection of JEK2 into the Slovenian power system will increase the capability of the system of voltage regulation and stability. JEK2 1100 MW does not represent a cause for contingency in the transmission system of Slovenia. The transmission network is strong, the interconnections lines are underloaded and ready to increase cross-border flows even after the inclusion of the JEK2 1100 MW unit. The Slovenian power system is strongly dimensioned. From the point of view of stationary security analysis, it does not represent an obstacle in the connection of JEK2.

Dynamic analyses, which include the analysis of electromechanical transients (voltage and angular conditions in the event of rapid power outages), showed that the connection of JEK2 1100 MW from the dynamic point of view is feasible and secure for the power system, both in 2030 and in 2043.

The failure of NEK or JEK2 does not cause dynamic problems in the Slovenian power system, not in 2030, nor in 2043. The courses of every worst-case simulation themselves showed that the transient, frequency and voltage stability is maintained. The maximum frequency deviation was achieved after the NEK tripping and equals only 100 mHz. Bus voltages showed up to 2% relative deviation from the initial state; they remain within tolerance limits until the end of the transients. The rotor angles showed oscillations that slowly fade and stabilize after 40 s. Speed variations were negligibly small below 0.1%.

The worst-case critical clearing times of JEK2 are 200 ms in 2030 and 220 ms in 2043 which are significantly longer than the response time of the bus differential protection, thus the connection of JEK2 to the Krško substation is secure. The Slovenian power system is strongly connected to the entire ENSTO-E network with excellent single or double electrical HV connections. The small size of the Slovenian power system, yet with large sources and relatively short connections (up to 100 km) and consequently also with relatively small line impedances, is a reliable starting point for a stable power system operation.

In the light of estimation of the JEK2 maximal nominal electrical power we concluded that the connection of JEK2 2x1100 MW variant is feasible and secure for the power system, both in 2030, as well as in 2043. The maximum estimated threshold of JEK2 nominal net electrical power in the implementation of one individual generator unit is approximately 2000 MW in 2030 or 2200 MW in 2043.

JEK2 would significantly increase the electromechanical immunity of the electrical power system. The additional inertia of JEK2 would provide essential system capacity which is needed for development of the operation of renewable energy sources, which are unpredictable and lack the traditional inertia. To maintain the secure and stable energy system operation and simultaneous development of the state-of-the-art electrical inertia of distributed renewable sources, JEK2 as large, zero CO2 power source is needed.

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