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# Transmission Grid Resilience to Support NPP Operation

***Hrvatski operator prijenosnog sustava d.d.***
***System Operation Sector***
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- Resilience in general
- High impact low frequency events
- Power system resilience
- System operational resilience
- Transmission grid resilience
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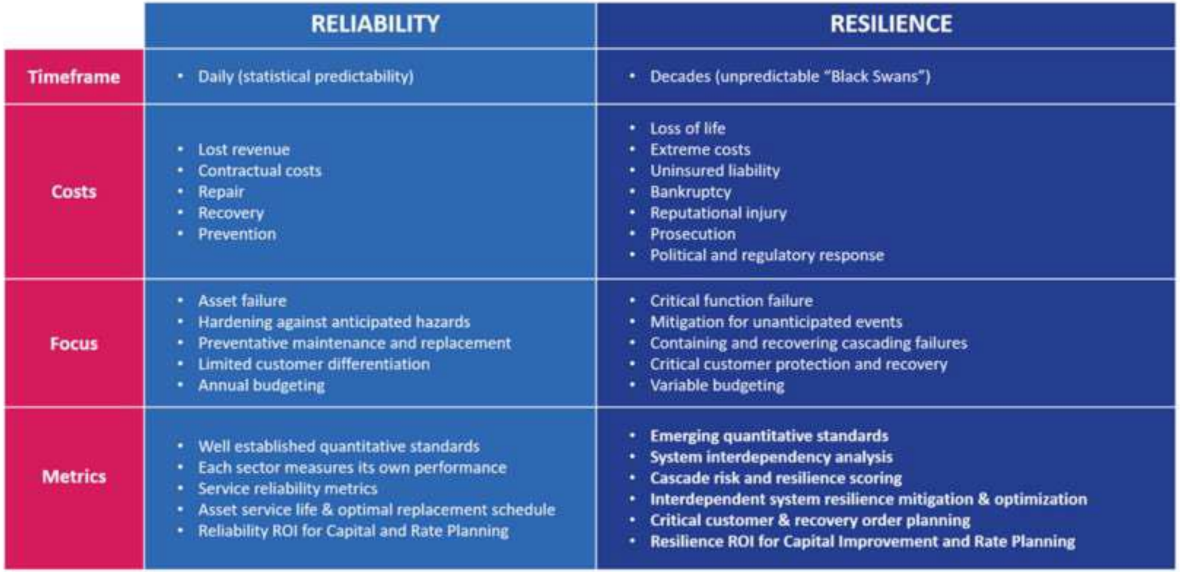
- Transmission grid resilience to support NPP operation

# Resilience in general

- The ability to become strong, healthy, or successful again after something bad happens,
- The ability to return to its original shape after it has been pulled, stretched, pressed, bent, etc.,
- The ability to plan and prepare for, absorb, respond to and recover from disasters and adapt to new conditions,
- The intrinsic ability of a system to maintain or regain a dynamically stable state, which allows it to continue operations after a major disruption and/or in the presence of a continuous stress,
- The ability of an organization to continue to provide business services in the face of adverse operational events by anticipating, preventing, recovering from, and adapting to such events.

# Reliability vs Resilience



| | RELIABILITY | RESILIENCE |
|---|---|---|
| **Timeframe** | • Daily (statistical predictability) | • Decades (unpredictable "Black Swans") |
| **Costs** | • Lost revenue<br>• Contractual costs<br>• Repair<br>• Recovery<br>• Prevention | • Loss of life<br>• Extreme costs<br>• Uninsured liability<br>• Bankruptcy<br>• Reputational injury<br>• Prosecution<br>• Political and regulatory response |
| **Focus** | • Asset failure<br>• Hardening against anticipated hazards<br>• Preventative maintenance and replacement<br>• Limited customer differentiation<br>• Annual budgeting | • Critical function failure<br>• Mitigation for unanticipated events<br>• Containing and recovering cascading failures<br>• Critical customer protection and recovery<br>• Variable budgeting |
| **Metrics** | • Well established quantitative standards<br>• Each sector measures its own performance<br>• Service reliability metrics<br>• Asset service life & optimal replacement schedule<br>• Reliability ROI for Capital and Rate Planning | • **Emerging quantitative standards**<br>• **System interdependency analysis**<br>• **Cascade risk and resilience scoring**<br>• **Interdependent system resilience mitigation & optimization**<br>• **Critical customer & recovery order planning**<br>• **Resilience ROI for Capital Improvement and Rate Planning** |

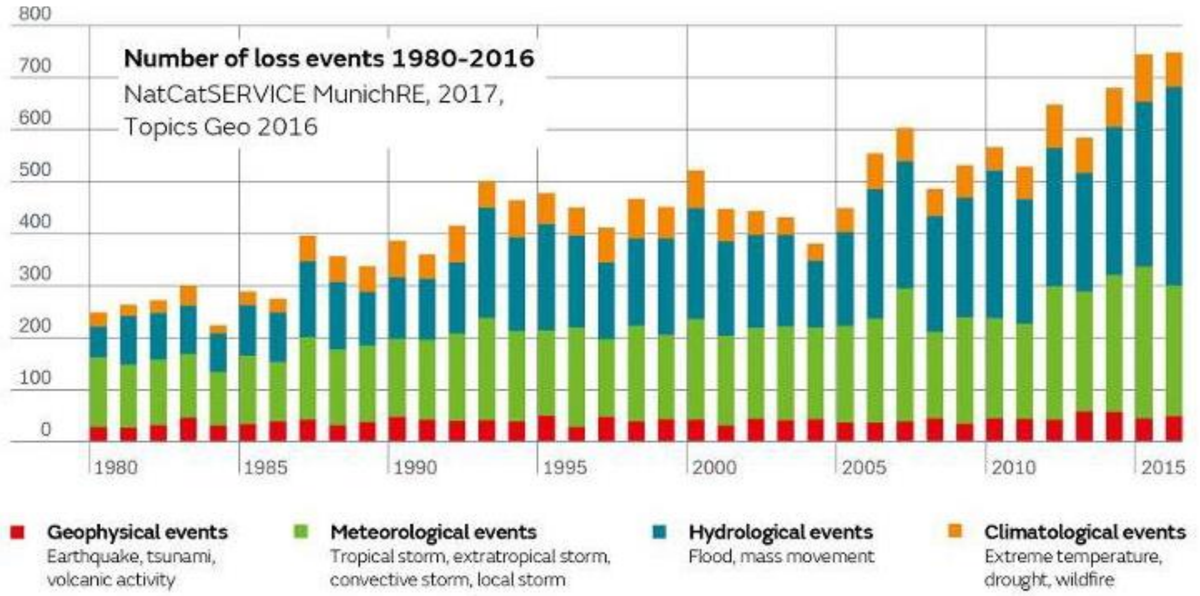
Reliability vs Resilience*

* Mouco, A., et al. "A Discussion of Resilience in Power Grids," Proc. CIGRE US National Committee 2023 Grid of the Future Symposium, 2023.

# High impact low frequency (probability) events

- High impact low frequency (HILF) events
  - **Physical – natural**: cyclones, drough, earthquakes / seismic events, floods, hurricanes / superstorms, land slides / avalanches, snow / ice storms, tsunami, wild fires, heat waves, solar / geomagnetic storms,
  - **Physical - man-made**: terrorist threats, physical security violations, vandalism, pandemics,
  - **Cyber threat**: malware, denial of service, man-in-the-middle
- HILF events occur very infrequently, generally have the potential to impact many assets at once, have catastrophic impacts on the bulk power system and society-at-large,
- Limited “real-world” operational experience with addressing HILF events risks.

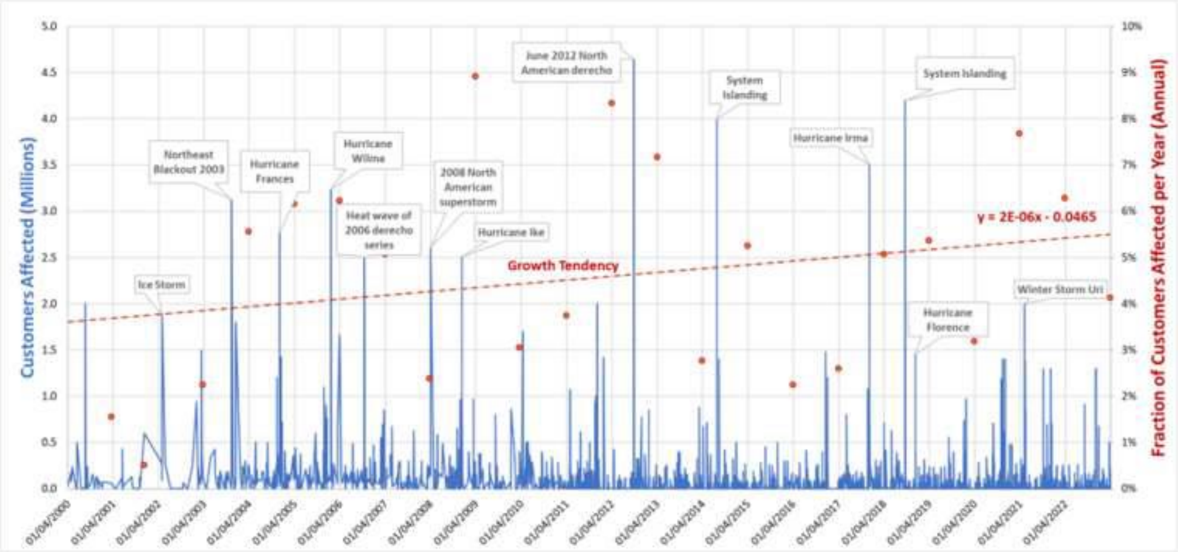
# Are HILF events becoming more frequent?



Increasing frequency of extreme climatic events worldwide, 1980 – 2015.*

*CIGRE TB 833 - Operating strategies and preparedness for system operational resilience

# Electrical power system customers affected by HILF events

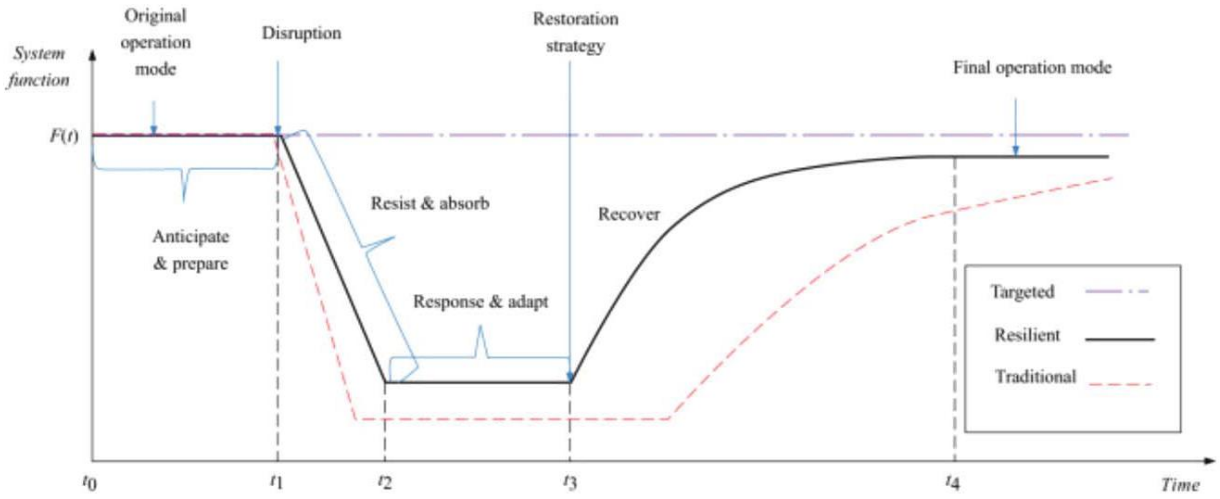


US Blackouts and Power Outages Affecting Transmission & Distribution Assets 2000 – 2022., US Department of Energy Annual Summary *

* Mouco, A., et al. “A Discussion of Resilience in Power Grids,” Proc. CIGRE US National Committee 2023 Grid of the Future Symposium, 2023.

# Power system resilience

- The ability to limit the extent, severity and duration of system degradation following an extreme event (CIGRE Working Group C4.47 - Power System Resilience)



Resilient power system trapezoid

# Super storm, Croatia, July 2023.



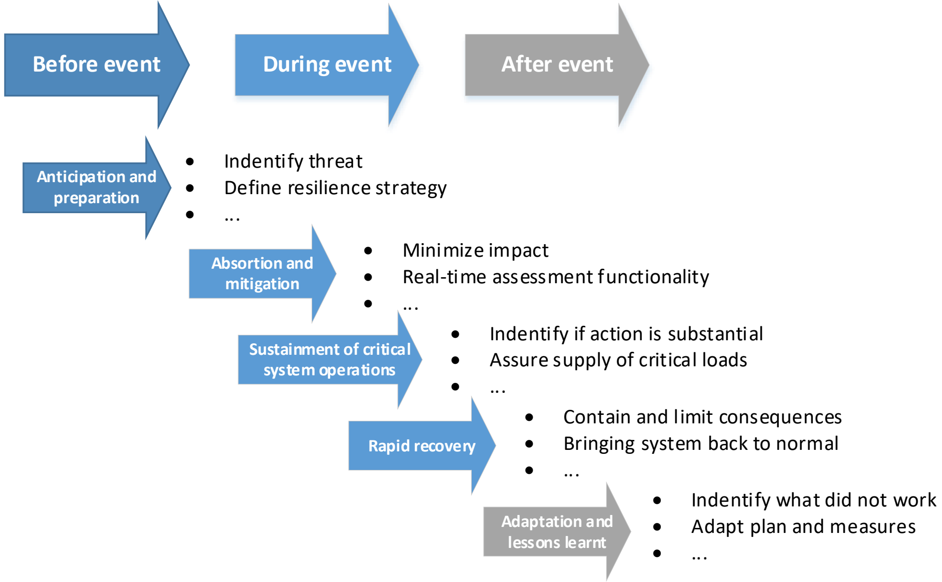



# System operational resilience

- Power system resilience as the ability to respond quickly to and recover from a disruption sometimes also referres to **system operational resilience**,
- Operational resilience extends beyond transmission system and is a **whole-of-grid approach**,
- Operational resilience are based mainly on **Defence, Emergency and Restoration Plans** developed by Transmission System Operators (TSO), but highlighting among others the role of the Distribution System Operators (DSO).

# Sequence and steps of system operational resilience

- System operational resilience is achieved through a set of measures to be taken before, during, and after extreme events, such as: anticipation, preparation, absorption, sustainment of critical system operations, rapid recovery, adaptation, and application of lessons learnt.*



**Before event** → **During event** → **After event**

**Anticipation and preparation**
- Indentify threat
- Define resilience strategy
- ...

**Absortion and mitigation**
- Minimize impact
- Real-time assessment functionality
- ...

**Sustainment of critical system operations**
- Indentify if action is substantial
- Assure supply of critical loads
- ...

**Rapid recovery**
- Contain and limit consequences
- Bringing system back to normal
- ...

**Adaptation and lessons learnt**
- Indentify what did not work
- Adapt plan and measures
- ...

*CIGRE TB 833 - Operating strategies and preparedness for system operational resilience

# Transmission grid resilience

- Transmission grid resilience refers to the ability of the power transmission network to withstand and quickly recover from disruptions, such as extreme weather events, cyberattacks, equipment failures, or other unforeseen circumstances, while maintaining the reliable delivery of electricity to consumers.
- Key aspects of transmission grid resilience include:
  1. **Redundancy**: Having backup systems, alternative routes, or spare equipment in place to mitigate the impact of failures or outages in the grid infrastructure.
  2. **Flexibility**: The ability of the grid to adapt to changing conditions and demands, such as integrating renewable energy sources, managing fluctuations in supply and demand, and adjusting to unforeseen events.
  3. **Robustness**: Designing the grid infrastructure to withstand extreme conditions, such as high winds, storms, earthquakes, or other natural disasters, without significant damage or disruption.
  4. **Monitoring and Control Systems**: Implementing advanced monitoring, automation, and control systems to detect and respond to disruptions in real-time, minimizing downtime and maximizing grid reliability.
  5. **Cybersecurity**: Protecting the grid infrastructure from cyber threats and attacks, including securing control systems, communication networks, and data, to prevent unauthorized access or manipulation of critical systems.

# Enhancing transmission grid resilience

- Enhancement of transmission grid resilience requires:
  - collaboration among utilities, energy regulators, policymakers, technology providers, and other stakeholders to invest in infrastructure upgrades,
  - adopt best practices in grid operation and maintenance, and
  - implement robust risk management strategies.
- Increasing the use of renewable energy sources, distributed generation sources, energy storage, and other innovative technologies can contribute to a more resilient and sustainable energy system.

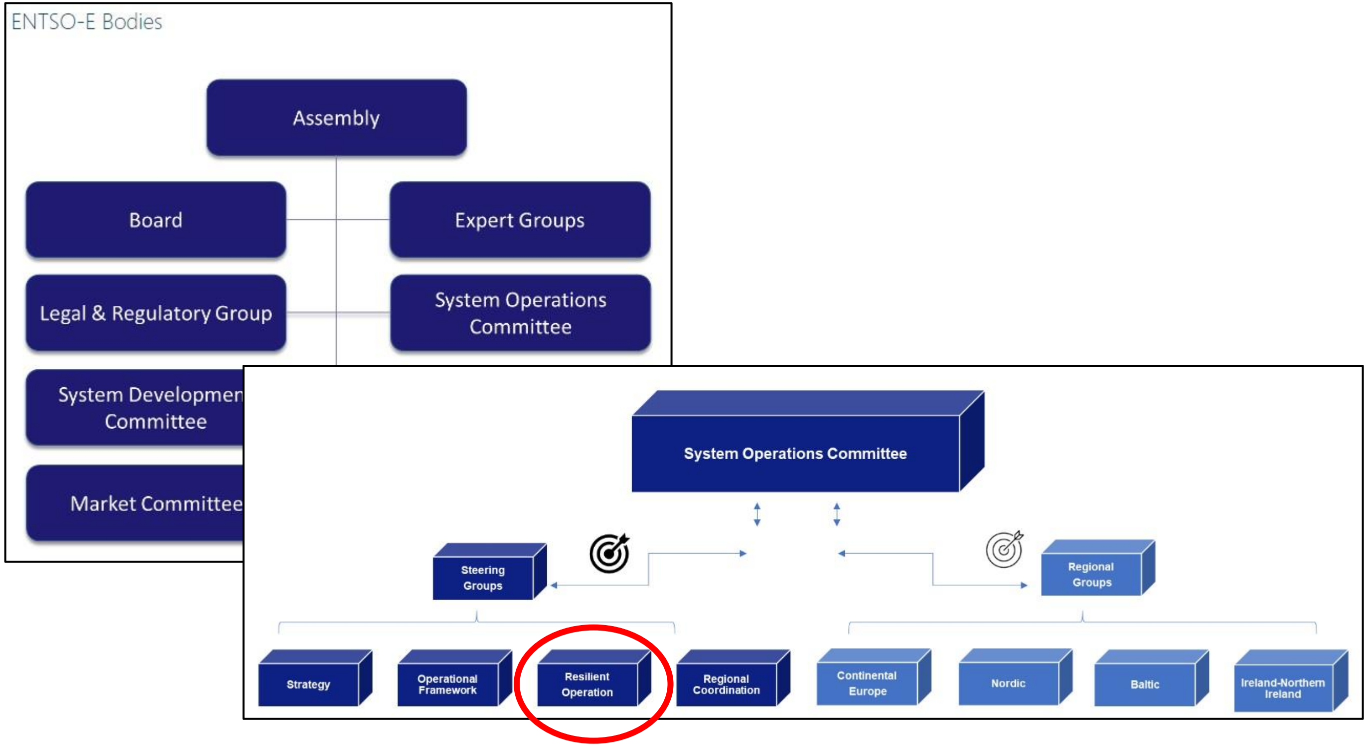
# Resilience measures usually adopted in practice

- Backup/Alternative Control Center,
- Backup power supply,
- Coordinated plans/procedures with law enforcement authorities and nearby utilities,
- Emergency Response Center / Crisis rooms,
- Regular training of operators,
- Reliable communication tools (e.g. backup communication like satellite phones),
- Spare Equipment Tailored for the Events (e.g. autotransformers, transmission towers, etc.),
- Special Protection Schemes,
- Written operational plans and procedures,
- ….

# Resilience measures for future decarbonized power systems

- Flexibility increase through the active participation of customers and usage of energy storage technologies, together with establishment of multi-energy system,
- System inertia increase through the use of grid forming inverters,
- Forecasting of extreme weather events with grid impact assessment through the use of AI,
- Using of HILF data for grid development methodologies.

# ENTSO-E structure
# The importance of resilient system operation is recognised



# Steering Group Resilient Operation

The main objective of the Resilient Operation is to maintain the high standard of interoperability, reliability and security of operation of the European electricity transmission systems, while resolving the increasing complexity and challenges, which include reduced system inertia, increased adequacy risks, and widespread digitalisation.

## Working Groups

- Incident Classification Scale (ICS WG)
- Load-Frequency Control (ALFC WG)
- Inter-Synchronous Area (ISA WG)
- Protection Equipment (PE WG)
- Risk Preparedness (RP WG)
- Critical System Protection (CSP WG)
- Resilience of Cyber-Physical System (R-CPS WG)
- Operational Group (OG) *restricted access
- ENTSO-E Awareness System (EAS CT)

## Projects

- Manually-Controlled Load Shedding Project (MCLS)
- Voltage Management Project (VMP)
- Closed Projects Archive

## Grid Incidents Investigations

- Major Grid Incidents
- Local Grid Incidents
- Implementation of Recommendations

# Transmission grid resilience to support NPP operation

- Resilient NPP operation is an important part of **electric grid resilience** and vice versa, resilient electrical grid operation is an indivisible part of **NPP resilience**,
- Stable and resilient grid operation is supporting normal NPP operation, as well as stable NPP startup and shutdown, including NPP **emergency events**,
- NPP are normally required to have multiple sources of electricity, including a minimum of two independent **offsite power sources** (i.e. two connections from the transmission system to the NPP), and **onsite power sources** (typically a combination of batteries and diesels or small gas turbines),
- Close **collaboration** between the NPP operator and TSO is required,
- **Use case**: resilient transmission grid operation supporting stable operation of NPP Krško (1 x 696 MW),

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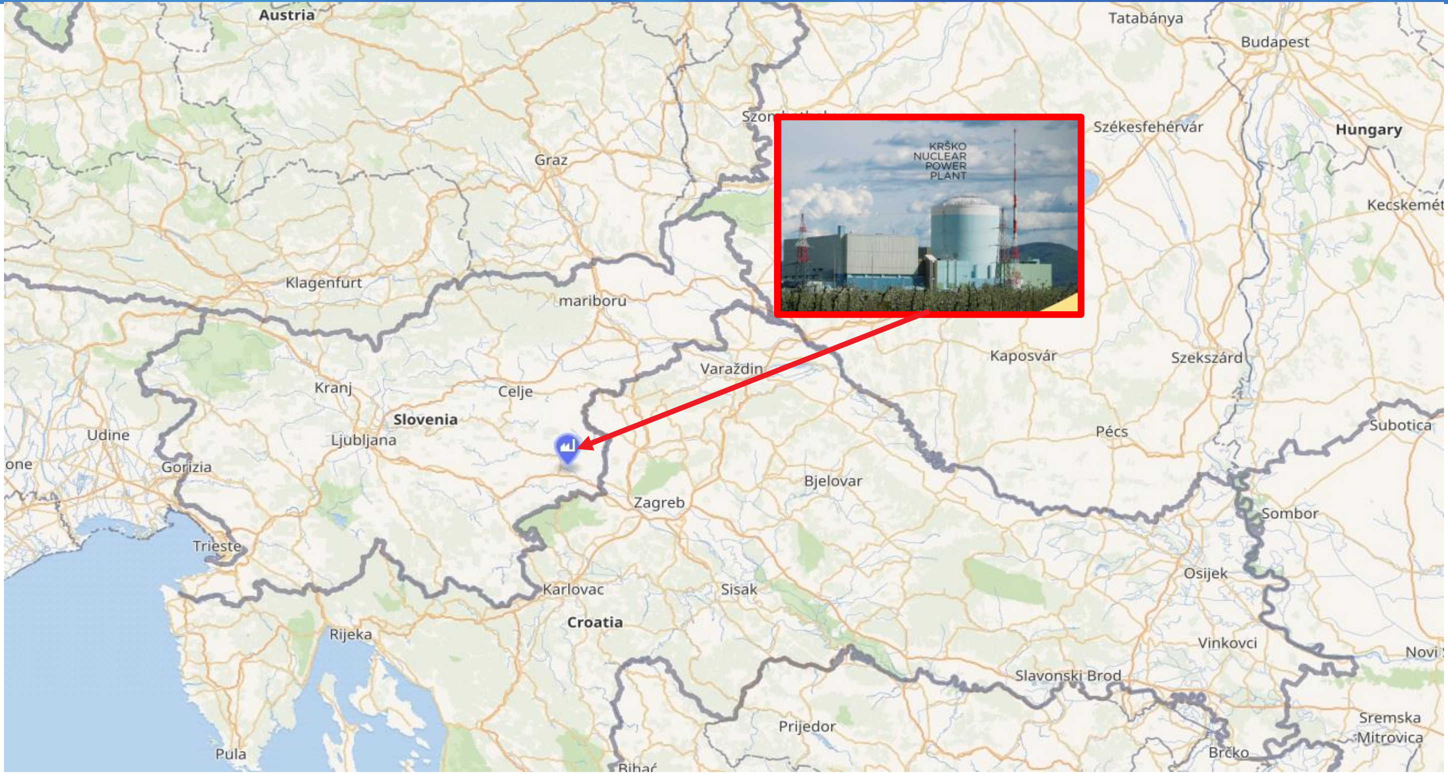
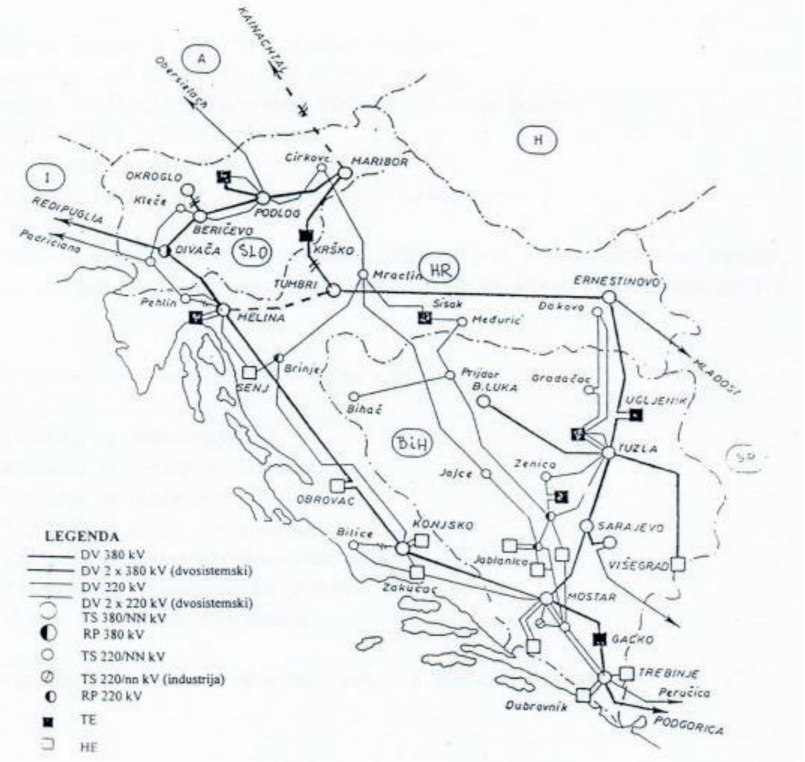
# NPP Krško geographical location



# Power system of the western part of the former Yugoslavia in 1990. (Nikola Tesla Ring)



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# Croatian transmission system – important dates in the context of NPP Krško

- 1974. Start of the 400 kV network construction
- 1977. SS 400/110 kV Ernestinovo put into operation
- 1978. The 400 kV network was built in the form of a ring connecting all areas of former Yugoslavia. The northern main line of the network 400 kV Obrenovac (Serbia) - Ernestinovo (Osijek) -Tumbri (Zagreb) - Maribor (Slovenia) was put into operation.
- 1979. The southern line of the 400 kV network Mostar (Bosnia and Herzegovina) - Konjsko (Split) - Melina (Rijeka) - Divača (Slovenia) is in operation.

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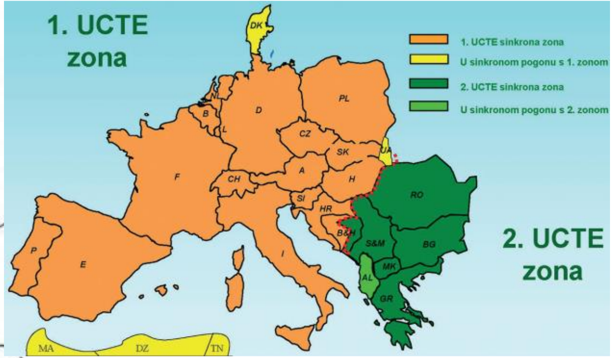
# Slovenian transmission system – important dates in the context of NPP Krško

- 1972.The beginning of the 400 kV Nikola Tesla transmission network construction as part of the unified network of the former Yugoslavia
- 1976.The 400/110 kV substation in Maribor and the 400 kV power lines linking Maribor-Podlog and Maribor-Krško-Tumbri border are included in the Slovenian electric power system
- 1981.400 kV Divača – Redipuglia (Italy)

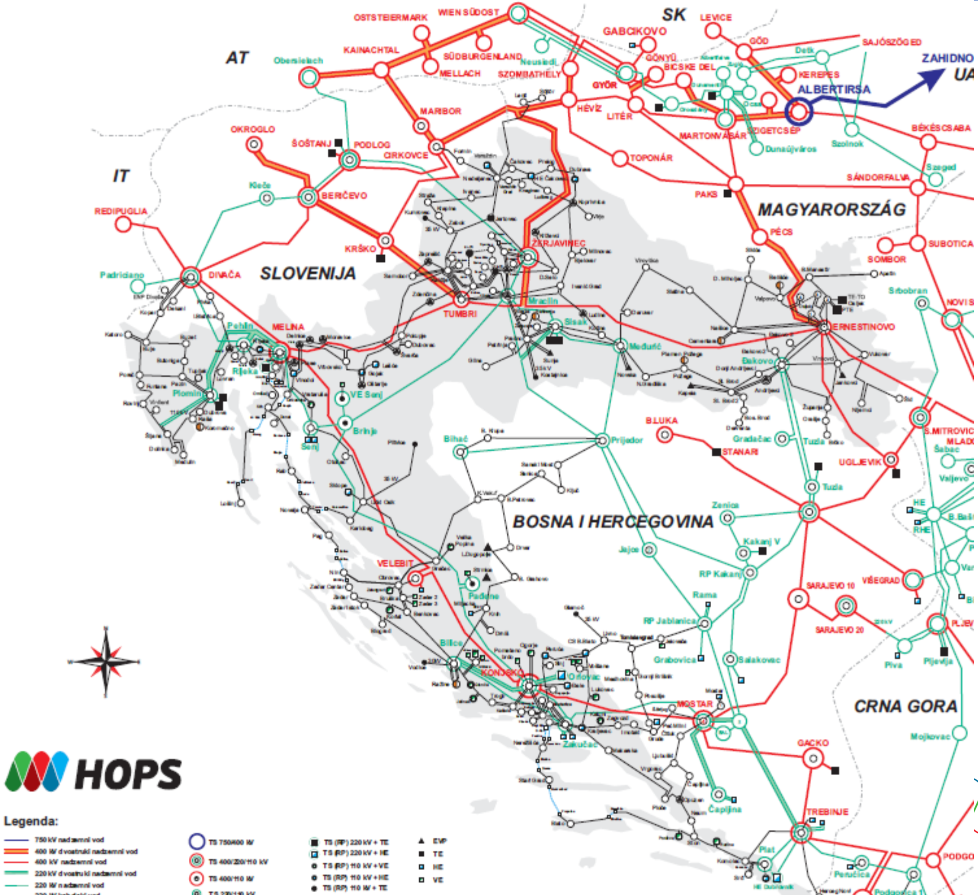
# Power system of the western part of the former Yugoslavia in 1991.



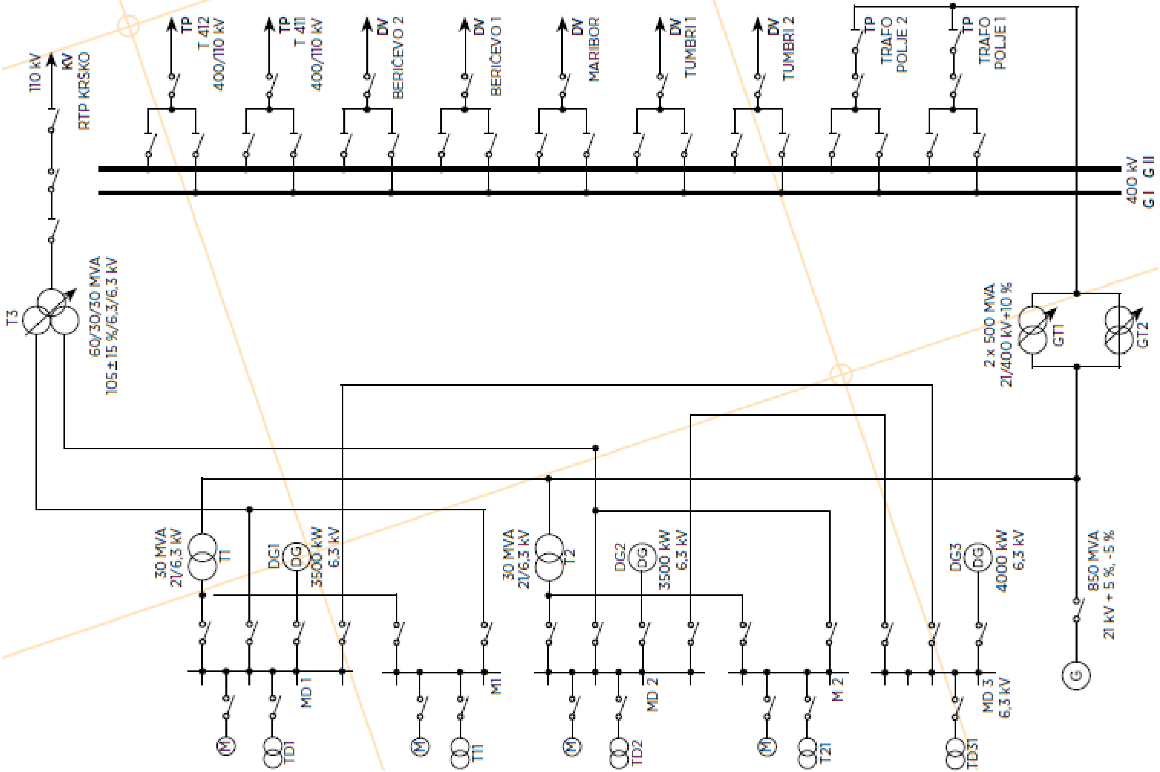
# Transmission system reinforcement after 1990.

- 1992 Completion of the construction of the 400 kV Melina (Rijeka) - Tumbri (Zagreb) line
- 1999 2x400 kV Tumbri (Zagreb) - Heviz (Hungary) put into operation
- 2003 SS 400/110 kV Ernestinovo rebuilt
- 2004 The construction of SS 400/220/110 kV Žerjavinec.
- 2004 I and II synchronous zones of UCTE were reconnected
- 2010 2x400 kV Ernestinovo – Pecs (Hungary) put into operation
- 1992 2 x 400 kV Maribor – Kainachtal (Austria)
- 2014 2 x 400 kV Beričevo–Krško

# Slovenian and Croatian transmission system today



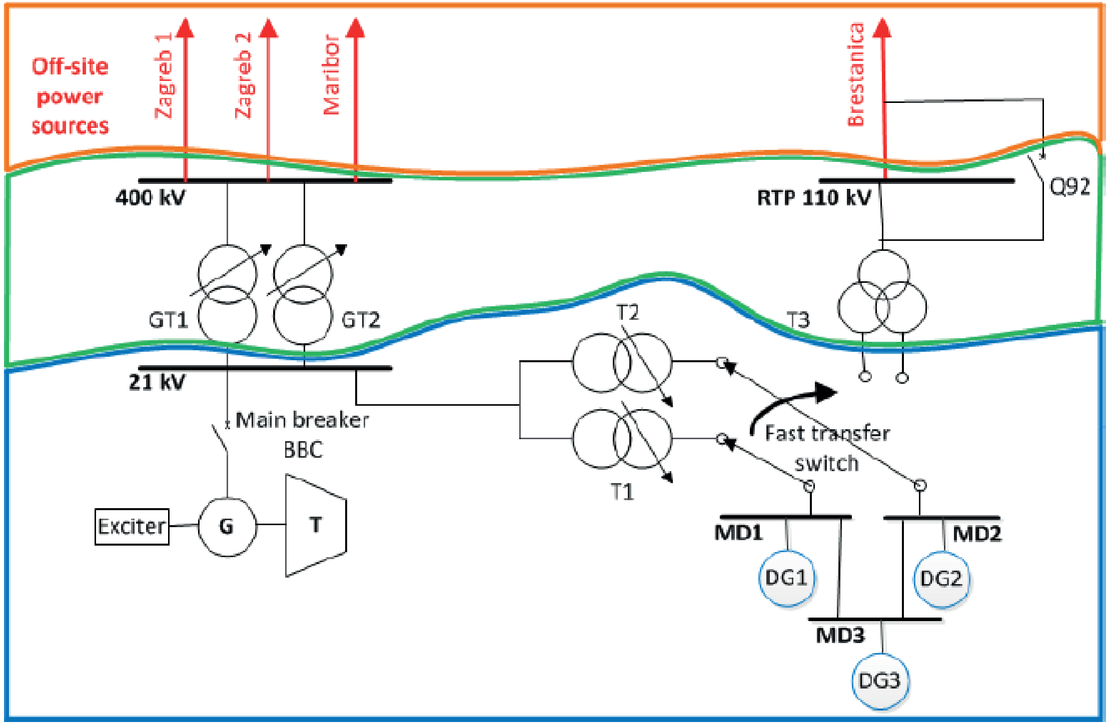
# NPP Krško grid connection design



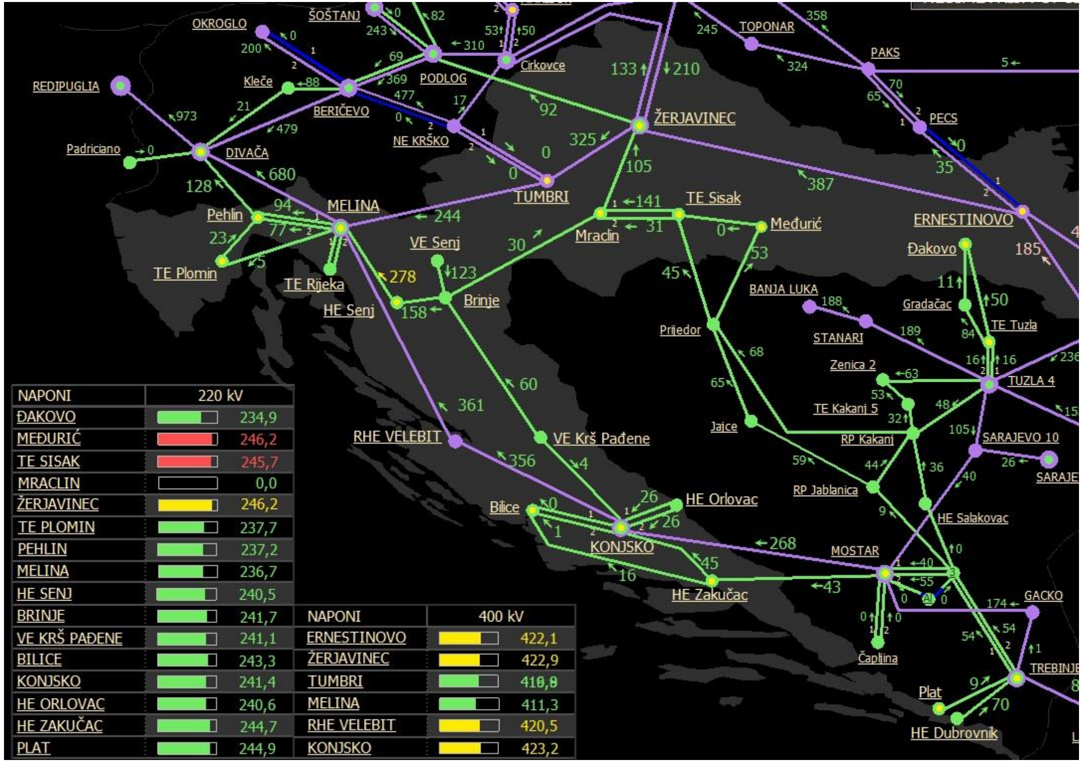
# NPP Krško house load supply

- NPP Krško house load is supplied either from its generator or 400 kV transmission system,
- The electric power is supplied through the 110 kV cable from the SS Krško 400/110 kV. The backup supply of electric power is assured from the **Brestanica Gas-steam Power Plant**, which is 7 km away from the NPP Krško. Brestanica Power Plant can cut-off all other consumers and supply the power only to the NPP Krško (black start in 20min),
- In addition, the plant is provided with three diesel generators (DG), each with rated power of **3500 kW**, which serve as an independent emergency electric power source for essential plant systems and are able to respond in 10 seconds already. The maximum operation duration of the DGs is seven **(7) days**.

# NPP Krško electrical grid connection and supply



# NPP Krško – important for voltage/var control



| NAPONI | 220 kV | |
|---|---|---|
| ĐAKOVO | 🟩 | 234,9 |
| MEĐURIĆ | 🟥 | 246,2 |
| TE SISAK | 🟥 | 245,7 |
| MRACLIN | | 0,0 |
| ŽERJAVINEC | 🟨 | 246,2 |
| TE PLOMIN | 🟩 | 237,7 |
| PEHLIN | 🟩 | 237,2 |
| MELINA | 🟩 | 236,7 |
| HE SENJ | 🟩 | 240,5 |
| BRINJE | 🟩 | 241,7 |
| VE KRŠ PAĐENE | 🟩 | 241,1 |
| BILICE | 🟩 | 243,3 |
| KONJSKO | 🟩 | 241,4 |
| HE ORLOVAC | 🟩 | 240,6 |
| HE ZAKUČAC | 🟩 | 244,7 |
| PLAT | 🟩 | 244,9 |

| NAPONI | 400 kV | |
|---|---|---|
| ERNESTINOVO | 🟨 | 422,1 |
| ŽERJAVINEC | 🟨 | 422,9 |
| TUMBRI | 🟩 | 410,8 |
| MELINA | 🟩 | 411,3 |
| RHE VELEBIT | 🟨 | 420,5 |
| KONJSKO | 🟨 | 423,2 |

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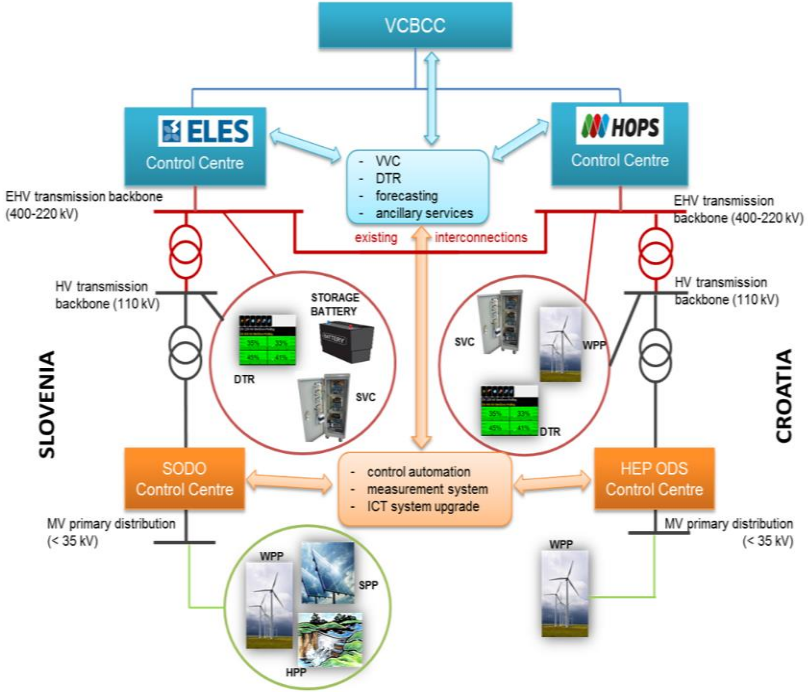
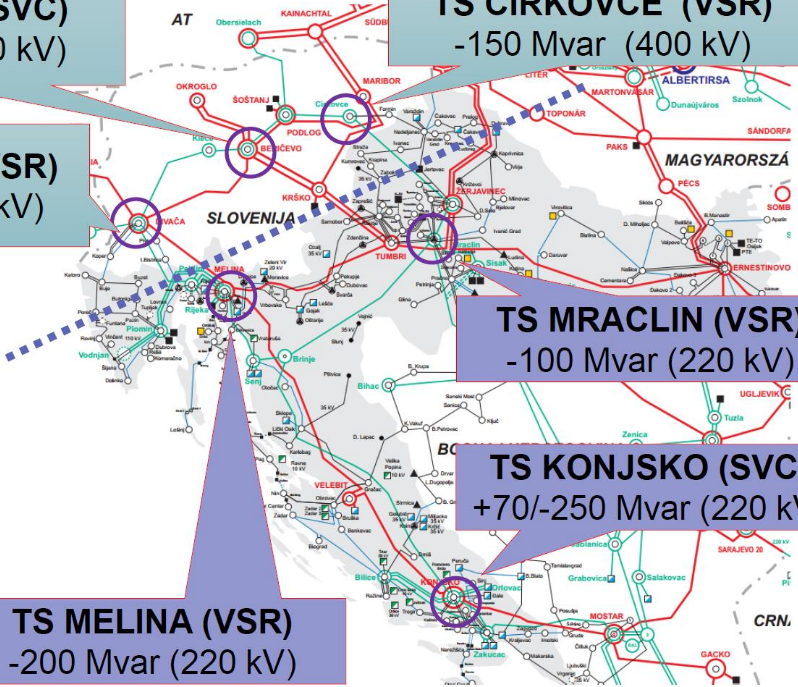
# SINCRO.GRID – cross-border smart grid project for coordinated voltage/var control



Coordinated voltage/var control system

- SINCRO.GRID is a **smart grid** project of Croatian and Slovenian TSOs (**HOPS** and **ELES**) and two DSOs (**HEP ODS** and **SODO**), destined towards better integration of regional electricity markets, increase of security of supply and creation of preconditions for **increase of RES** share on the market,
- **Project of Common interest**, co-financed from the Connecting Europe Facility – **CEF**, amounting 40.5 mil. € (51 % of investment), of which 13.5 mil. € in HOPS’s network
- Project completed in **2022.**

# SINCRO.GRID – reactive power compensation devices



**TS BERIČEVO (SVC)**
+/- 150 Mvar (400 kV)

**TS CIRKOVCE (VSR)**
-150 Mvar (400 kV)

**TS DIVAČA (MSC + VSR)**
+100/-150 Mvar (400 kV)

**Slovenija**
Σ = + 250/-450 Mvar

**TS MRACLIN (VSR)**
-100 Mvar (220 kV)

**TS KONJSKO (SVC)**
+70/-250 Mvar (220 kV)

**Hrvatska**
Σ = +70 /- 550 Mvar

**TS MELINA (VSR)**
-200 Mvar (220 kV)

# NPP Krško – other important operational aspects

- NPP Krško contributes significantly to the **power system stability** and **inertia**, what will be specially valuable considering future operational conditions, when more and more energy resources will be connected to the grid through the **inverters**,
- NPP Krško, as a largest single generator in control block of Slovenia, Croatia and Bosnia and Hezegovina, sets the need for control block **frequency restoration reserve power** – important aspect to have in mind when developing NPP projects, specially for small countries with limited power reserves.

# HILF event – earthquake 29/12/2020

- On **December 29, 2020**, at 12:19:54, an **earthquake** of magnitude 6.2 ML hit central Croatia,
- Distance from the epicenter of the earthquake to NPP Krško was **85 km**,
- About **20s** after the earthquake, the seismic instrumentation at the NPP Krško detected the first earthquake shocks (0.01g), after which there were significant fluctuations and the **automatic shutdown** of the reactor from full power,
- The automatic shutdown occurred due to the operation of the **reactor protection** on a negative change in neutron flux greater than 8% / 2 sec on the off-core instrumentation.

# HILF event – earthquake 29/12/2020

- Grid events related to the earthquake:
  - Tripping of 400kV OHL Tumbri – Krško 1,
  - Tripping of several 220 and 110 kV OHLs,
  - 11 substations owned by HOPS suffered damage,
  - Substations' damage caused load shedding (~ 215 MW), which reduced the need for reserve generation to compensate the NPP Krško outage.

# Thank you for your attention!

**Hrvatski operator prijenosnog sustava d.d.**

**www.hops.hr**