Analysis of the Two Systems Splits in the Continental European Synchronous Area in year 2021

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Outline

- ENTSO-E SubGroup System Protection and Dynamics (SPD)
- Wide Area Monitoring Systems in Europe
- Significant events in CE synchronous area in 2021:
  - January 8th, 2021 14h05
  - July 24th, 2021 16h35
  - October 11th, 2021 11h55

For each event:
- System conditions before the incident
- Sequence of events
- Activation of automatic and manual countermeasures
- Frequency back to 50 Hz
- Technical analysis
- Derived recommendations

Conclusions
Setup and maintenance of CE power system dynamic models

Regularly and on demand perform dynamic analysis

Permanent monitoring of CE power system dynamic behaviour by using of distributed WAMs

Setup and development of required dynamic system analysis procedures

Recommend measures and improvements with respect to CE system dynamic behaviour

Cooperate and collaborate with system development WG, grid code development and research and new IT tools

Ongoing setup of public available documents reflecting the results of the WG work

Highly active participation on the analysis and reporting of significant CE wide events
Wide Area Monitoring Systems (WAM) in Europe

- Success story of synchronised and decentralised approach by using in parallel different tools but one common aim
- Combination of on-line and offline approach
- Interfacing with dynamic model tools / calibration
- Participation on state-of-the-art documentation, standardisation – e.g. CIGRE WG
- Use of WAM system recordings together with digital protection or transient recorder measurements for in-depth system analysis
SPD WAMTOOL GUI / MAIN WINDOW

Measurements

Modal Analysis

FFT

Single-Sided Amplitude Spectrum of Signal(t)

Signal filtering

Kalman filter

FFT / spectrum

Export

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SPD WAMTOOL GUI / EXEMPLARY FUNCTIONALITIES

Detailed Visual Check

Spectrum Analysis

Modeshapes

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System Split 8 January 2021

Behaviour after system separation & activated automatic countermeasures

Manual countermeasures and system stabilization

Resynch

Situation before

Sequence of events
System Conditions before the Incident

- High active power flow from East to West
- Operation of transmission system on the edge
- One single outage has driven the system to pass the transient stability limit
Overall situation was influenced by warm weather and orthodox Christmas holidays in South-East-Europe as well as a cold spell with high demand in North-West Europe

Market-based pan-European power exchange led to a high export from Balkan peninsula to Continental Europe of around ~3,900 MW+

Operation of transmission system on the edge
System Conditions before the Incident

- Rule of thumb:
  - The tie-lines Pecs1 and Pecs2 are not connected to the same busbar
  - The two transformers are not connected to the same busbar

- Planned outage of Pecs2 since 5 January 2021 (circuit breaker failure)

- The topology was not changed after the planned outage, counting on Control Room supervision of busbar coupler flows, protected by a overcurrent relay

- Flow from South (lines S. Mitrovica and Ugljevik) via busbar coupler to the North (lines Zerjaminec and Pecs1)

- One single outage have driven the system to pass the transient stability limit
<table>
<thead>
<tr>
<th>No</th>
<th>TSO</th>
<th>Delta [s]</th>
<th>trip time</th>
<th>substation 1</th>
<th>substation 2</th>
<th>Voltage [kV]</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>1a</td>
<td>HOPS</td>
<td>0</td>
<td>14:04:25.9</td>
<td>Ernestinovo</td>
<td></td>
<td>400</td>
<td>busbar coupler overload protection</td>
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<td>1b</td>
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<td>2.6</td>
<td>14:04:28.0</td>
<td>Ernestinovo</td>
<td></td>
<td>400/110</td>
<td>Overload protection of both 400/110 kV transformers</td>
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<td>2</td>
<td>EMS</td>
<td>23</td>
<td>14:04:48.9</td>
<td>Subotica</td>
<td>Novi Sad</td>
<td>400</td>
<td>overload protection 20 s 2nd zone</td>
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<tr>
<td>3</td>
<td>TRANS</td>
<td>26</td>
<td>14:04:51.9</td>
<td>Paroşeni</td>
<td>Târgu Jiu N</td>
<td>220</td>
<td>distance prot. starting zone 2.4 s</td>
</tr>
<tr>
<td>4a</td>
<td>TRANS</td>
<td>27.9</td>
<td>14:04:53.8</td>
<td>Reşiţa</td>
<td>Timişoara</td>
<td>220</td>
<td>dist. prot. 0.4 s</td>
</tr>
<tr>
<td>4b</td>
<td>TRANS</td>
<td>27.9</td>
<td>14:04:53.8</td>
<td>Reşiţa</td>
<td>Timişoara</td>
<td>220</td>
<td>dist. prot. 0.4 s, breaker L1 failure</td>
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<tr>
<td>5</td>
<td>NOS BiH</td>
<td>28.2</td>
<td>14:04:54.1</td>
<td>Prijedor</td>
<td>Međurić</td>
<td>220</td>
<td>dist. prot. out-of-step protection</td>
</tr>
<tr>
<td>6</td>
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<td>28.2</td>
<td>14:04:54.1</td>
<td>Prijedor</td>
<td>Sisak</td>
<td>220</td>
<td>dist. prot. out-of-step protection</td>
</tr>
<tr>
<td>7</td>
<td>HOPS</td>
<td>28.3</td>
<td>14:04:54.2</td>
<td>Melina</td>
<td>Velebit</td>
<td>400</td>
<td>dist. prot. zone 3</td>
</tr>
<tr>
<td>8</td>
<td>TRANS</td>
<td>28.3</td>
<td>14:04:54.2</td>
<td>Mintia</td>
<td>Sibiu</td>
<td>400</td>
<td>distance prot. power swing cond.</td>
</tr>
<tr>
<td>9</td>
<td>HOPS</td>
<td>28.5</td>
<td>14:04:54.4</td>
<td>Brinje</td>
<td>Padene</td>
<td>220</td>
<td>dist. prot. zone 1</td>
</tr>
<tr>
<td>10</td>
<td>TRANS</td>
<td>28.6</td>
<td>14:04:54.5</td>
<td>Gădălin</td>
<td>Iernut</td>
<td>400</td>
<td>distance prot. power swing cond. zone 2 0.4 s</td>
</tr>
<tr>
<td>11</td>
<td>TRANS</td>
<td>28.7</td>
<td>14:04:54.6</td>
<td>Sibiu Sud</td>
<td>Iernut</td>
<td>400</td>
<td>dist. prot. zone 3 reverse 0.6 s</td>
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<tr>
<td>12</td>
<td>TRANS</td>
<td>28.7</td>
<td>14:04:54.6</td>
<td>Roşiori Autotransf 400/220</td>
<td></td>
<td>400/220</td>
<td>dist. prot. power swing cond.</td>
</tr>
<tr>
<td>13</td>
<td>TRANS</td>
<td>42.6</td>
<td>14:05:08.5</td>
<td>Iernut</td>
<td>Câmpia Turzii</td>
<td>220</td>
<td>dist. prot. zone 2 power swing conditions</td>
</tr>
<tr>
<td>14</td>
<td>TRANS</td>
<td>42.7</td>
<td>14:05:08.6</td>
<td>Făntânele</td>
<td>Ungheni</td>
<td>220</td>
<td>dist. prot. zone 2 power swing conditions</td>
</tr>
</tbody>
</table>
Activation of Automatic and Manual Countermeasures

1.7 GW automatic interruptible services in France and Italy were disconnected

447 MW automatic supportive power from synchronous area Nordic and 57 MW from GB

4.7 GW automatic supportive power from synchronous area Nordic and 57 MW from GB

Activation of FCR

975 MW automatic disconnection of generation in TR

Stabilisation after 15 seconds

Interruptible services in Italy reconnect at 14:47 CET and in France at 14:48 CET

Reconnection at 15:07:31.6 CET

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Event technical analysis approach

- WAMS recordings (mainly voltage phasors)
- TSOs snapshots → complete nodal description and “dynamization” → voltage phase angle differences and protection behaviour analysis
- ENTSO-E transparency platform → one busbar mean frequency model → frequency transient reconstruction
- Transient recorder and digital protection device recordings → detailed analysis of trip causes
- SCADA recordings → primary and secondary frequency control, power flows before and after event
- Defence systems recordings → check of system balance
- All results converge on the physical presented explanation
Selected PMUs Location for Detailed Analysis

- Subotica 400 kV (RS)
- Ernestinovo 400 kV (HR)
- Divaca 400 kV (SI)
- Lavorgo 400 kV (CH)
- S. Mitrovica 400 kV (RS)
- Podgorica 400 kV (ME)
- Hamitbat 400 kV (TK)

8 January 2021

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Angular instability in CE power system

WAMs recordings

Angle difference between inertia centres East/West

Simulation confirms recordings behaviour

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Detailed Analysis

Frequency peaks:
• South-East area: 50.6 Hz
• North-West area: 49.74 Hz

Steady-state frequencies after separation

RoCoF: North-West = -60 mHz/s
South-East = +300 mHz/s

North-western area balance
South-East: **4668 MW** generation trip
3200 MW non-conform; 600-800 MW embedded gen.
Activation of Automatic and Manual Countermeasures NW Area

SPS: 1280 + 382 = 1662 MW
EPC: 57 + 447 = 504 MW
SPS + EPC = 2166 MW

FCR = 2826 MW
Load shed.: 36 MW
Self reg.: 987 MW
Gen. Shed.: 973 MW (341 MW dist. gen)
Detailed Analysis

18 January 2021
System modelling – Dynamic single busbar model

Modelling hypothesis North-West(*):
- System load: 326.2 GW
- Active power deficit: 6300 MW

Modelling hypothesis South-East(*):
- System load: 70.6 GW
- Active power surplus: 6300 MW

(*)... considering load and generation data from ENTSO-E Transparency Platform
System modelling – Detailed dynamic model model

- Single TSOs snapshots (static) ➔ Complete system snapshot ➔ Dynamization

- Very good dynamic correspondence
- Same no return point like found recordings
- After no return point simulated protections trip due to transient instability
- After no return point in case of no protection simulation West and East loss step
Expert Panel - Derived Recommendations

21 Recommendations derived in total. Most relevant are:

• The substation topology should be chosen in such a way that the flow through the busbar coupler is as low as possible. This should also be reflected in any TSO guidelines within the company where rules for the substation’s topology are described.

• Each TSO must transpose the set points of the protection equipment to operational security limits.

• The alarm levels must be clearly defined and shall be consistent for all network elements.

• For critical transmission system corridors, the stability margin must be assessed in operational planning and real-time operations.

• It should be mandatory to include outages of any transmission elements (incl. busbar couplers) in the contingency lists.
On 24th July 2021 at 16:36 CET, the Continental Europe Synchronous Area was separated into two areas due to cascaded trips of several transmission network Elements starting at the opening of a double circuit in France. The Iberian Peninsula (Spain and Portugal), was separated from the rest of CE. Resynchronisation was achieved at 17:09 CET.
System Conditions before the Incident

- Fire in the Moux area (south of FR) on 24 July 2021, at approximately 13:30
- 2544 MW power flow from France to Spain
Sequence of Events

<table>
<thead>
<tr>
<th>No</th>
<th>TSO</th>
<th>Delta [s]</th>
<th>Trip time</th>
<th>Substation 1</th>
<th>Substation 2</th>
<th>Voltage [kV]</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>RTE</td>
<td>0</td>
<td>16:33:12.0</td>
<td>Baïcas (FR)</td>
<td>Gaudière (FR)</td>
<td>400</td>
<td>Two phase fault. Circuit 2. Differential protection</td>
</tr>
<tr>
<td>2</td>
<td>RTE</td>
<td>131.8</td>
<td>16:35:25.8</td>
<td>Baïcas (FR)</td>
<td>Gaudière (FR)</td>
<td>400</td>
<td>Two phase fault. Circuit 1. Differential protection</td>
</tr>
<tr>
<td>3</td>
<td>RTE</td>
<td>205.0</td>
<td>16:36:37.0</td>
<td>Angia (FR)</td>
<td>Cantegril (FR)</td>
<td>400</td>
<td>Overload protection 60 s</td>
</tr>
<tr>
<td>4</td>
<td>REE</td>
<td>206.9</td>
<td>16:36:38.0</td>
<td>Bliescas (ES)</td>
<td>Pragnieres (FR)</td>
<td>220</td>
<td>Distance protection zone 2 out-of-step condition</td>
</tr>
<tr>
<td>5</td>
<td>REE</td>
<td>207.2</td>
<td>16:36:39.2</td>
<td>Puerto de la Cruz (ES)</td>
<td>Beni Harchen (MA)</td>
<td>400</td>
<td>Underfrequency protection on Moroccan end that sent a direct transfer trip to Spanish end</td>
</tr>
<tr>
<td>6</td>
<td>REE</td>
<td>207.5</td>
<td>16:36:39.5</td>
<td>Puerto de la Cruz (ES)</td>
<td>Meknassa (MA)</td>
<td>400</td>
<td>Underfrequency protection on Moroccan end that sent a direct transfer trip to Spanish end</td>
</tr>
<tr>
<td>7</td>
<td>RTE/REE</td>
<td>208.4</td>
<td>16:36:40.4</td>
<td>Angia (FR)</td>
<td>Arkale (ES)</td>
<td>220</td>
<td>Out-of-step protection (simultaneous on both sides)</td>
</tr>
<tr>
<td>8</td>
<td>RTE</td>
<td>209.3</td>
<td>16:36:41.3</td>
<td>Angia (FR)</td>
<td>Hemani (ES)</td>
<td>400</td>
<td>Out-of-step protection</td>
</tr>
</tbody>
</table>
Selected PMUs Location for Detailed Analysis

Avelin 400 kV (FR)
Tavel 400 kV (FR)
Saucats 400 kV (FR)
Biescas 220 kV (ES)
Hernani 400 kV (ES)
Recarei 400 kV (PT)
Le Cereal 400 kV (ES)
Vic 400 kV (ES)

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Complete Event Overview

24 July 2021

#1 400 kV Baixas-Gaudiere 2
#2 400 kV Baixas-Gaudiere 1
#3 400 kV Argia-Cantegrit

Voltage instability started

** - Avelin (FR) phase angle ref.
* Load reconnection is not reported

(1) 16:33:12 (2) 16:35:23.8 (3) 16:36:37
**Voltage collapse started**

- voltage degradation visible
- voltage phase angle increase
- coils start to be disconnected
- first generation got lost
Biescas (ES) 220 kV remains connected to the northern system!

- Total Load shed: 4872 MW
  - REE 3561 MW
  - REN 1246 MW
  - RTE 65 MW

- Total Pump disc: 2302 MW
  - REE 1995 MW
  - REN 307 MW
  - RTE 0 MW

- Total Load/Pump shed: 7174 MW

(3) 16:36:37 → 400 kV Argia-Cantegrit
Due to early voltage issues the coils (capacitors) start to be disconnected (connected) already before pump/load shedding: -1440 Mvar (16:35:27 – 16:36:37)

Total Coils:
- REE +1750 MVAr
- REN 0
- RTE -144, +272 MVAr

Total Capacitors:
- REE 0
- REN 0
- RTE -339, +519 MVAr

Total Coil disc / Cap conn -2233 MVAr
Total Coil conn / Cap disc +2541 MVAr
Total Generators disc: 3764 MW
- REE 2674 MW
- REN 1016 MW
- RTE 74 MW

480 MW in ES and FR already before separation (16:30:00 - 16:36:37)

** - Avelin (FR) phase angle ref.
* Load reconnection is not reported
Detailed Analysis - Disconnections & Voltage Management

<table>
<thead>
<tr>
<th></th>
<th>tot</th>
<th>REE</th>
<th>REN</th>
<th>RTE</th>
<th>Before split</th>
<th>After split</th>
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</thead>
<tbody>
<tr>
<td>Gen Disc</td>
<td>MW</td>
<td>3764</td>
<td>2674</td>
<td>1016</td>
<td>74</td>
<td>480</td>
</tr>
<tr>
<td>Load Shed</td>
<td>MW</td>
<td>4872</td>
<td>3561</td>
<td>1246</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td>Pump</td>
<td>MW</td>
<td>2302</td>
<td>1995</td>
<td>307</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Coil Reac</td>
<td>-MVAr</td>
<td>128</td>
<td>-1750</td>
<td>0</td>
<td>-144</td>
<td>-1150</td>
</tr>
<tr>
<td></td>
<td>+MVAr</td>
<td></td>
<td>+1750</td>
<td>0</td>
<td>+272</td>
<td>0</td>
</tr>
<tr>
<td>Capacitor</td>
<td>-MVAr</td>
<td>180</td>
<td>0</td>
<td>0</td>
<td>-339</td>
<td>-290</td>
</tr>
<tr>
<td></td>
<td>+MVAr</td>
<td></td>
<td>0</td>
<td>0</td>
<td>+519</td>
<td>0</td>
</tr>
</tbody>
</table>

![Graphs showing Power Output and RTE](image)
Detailed Analysis - Resynchronisation Process

- Synchrocheck settings to be reviewed and adapted

- Avelin (FR) phase angle ref.

* Load reconnection is not reported
Detailed Analysis – Voltage Phase Angle Difference Heat Map

Heat map confirms the initial “stress” on the Mediterranean side of interconnection

between event #1 and #2

RoCoF automatic calculation by SPD WAMTOOL

between event #2 and #3

#1 400 kV Baixas-Gaudiere 2
#2 400 kV Baixas-Gaudiere 1
#3 400 kV Argia-Cantegrit

24 July 2021
Technical Analysis - LFDD Frequency and Voltage Recordings
Significant disconnection of distributed generation and load shifting due to meshed operation can be observed

All relays have reacted as expected and have finally saved by their reaction the Iberian island!
Technical Analysis - LFDD Frequency and Voltage Recordings

COMTRADE Recording Analysis

Protection (WF): $f_s = 48.70$ Hz; $U_B/U_N = 0.70$ [V13MS]

Arganda 220 kV; Station ZIV77319 - Device 102
(File: Arganda 703_Madrid2021-07-24T16_36_40Z_470000)
Sent: 07/24/21; 18:36-40.470000; $f_s = 559$ Hz

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Technical Analysis - LFDD Frequency and Voltage Recordings

Overlapped WAM & LFDD Measurements at Lowest Frequency
### Detailed Analysis - Voltage Stability – Voltage Magnitude Heat Map

#### Minimum voltages before separation between event #2 and #3

**#1 400 kV Baixas-Gaudiere 2**

**#2 400 kV Baixas-Gaudiere 1**

**#3 400 kV Argia-Cantegrit**

#### Maximum voltages after LFDD activation after event #3

![Heat Map](image)

(a) 16:36:32

![Heat Map](image)

(b) 16:37:40

24 July 2021

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The dynamic simulations allow an accurate reproduction of the event (good correspondence with PMU measurements) ➔ they are an important tool to endorse the main hypothesis of the system event and to verify the correct functioning of relays.
1. Reduce volume of non-conform generation tripping
   i. Improve TSO-DSO coordination for definition of protection settings
   ii. Improve monitoring and data collection process by developing clear specifications

2. Communication chain in case of external conditions impacting system operation
   i. Highlight which weather conditions are currently considered in the security analyses conditions
   ii. Highlight the associated operational procedures
   iii. Identify how to develop complementary processes

3. Investigate the opportunity to supplement important transit corridors with SPS functionality (in combination with automatic overload protection)
   i. Overload protection with 1-5 min threshold shall be complemented with SPS functionality e.g., based on a centralised industrial load shedding scheme
   ii. Coordination of DRS schemes with the protection schemes of neighbouring systems

4. Enhance monitoring of LFDD operation (Low Frequency Demand Disconnection)
   i. Improve TSO-DSO coordination on monitoring of relay settings and activation
   ii. Setup specifications on data collection and data exchange

5. Review synchrocheck settings for corridor lines
   i. Avoid synchronisation with inappropriate settings
Conclusions

- Importance of CE-wide cooperation for system operation and system development

- Dynamic issues are getting more important in scenarios close to real time which is being tackled by TSOs by means of new procedures and tools (Dynamic Stability Assessment) and data sources used in operation (WAM).

- The WAMS recordings available thanks to SPD (System Protection and Dynamics working group ENTSO-E) monitoring continuous activity played a very important role to validate simulations

- Overlapping of WAM & digital protection relay recordings (COMTRADE) gives an important inside about relay reaction time

- It is confirmed that Continental Europe continuous improving dynamic model is a key task in order to give answer to arising system needs.

- Follow-up activities based on event report recommendations will result in further power system operation improvements
References

- Final report on the separation of the Continental Europe power system on 8 January 2021 (entsoe.eu)
- Final report on the power system separation of Iberia from Continental Europe on 24 July 2021 (entsoe.eu)
Our values define who we are, what we stand for and how we behave. We all play a part in bringing them to life.

EXCELLENCE
We deliver to the highest standards. We provide an environment in which people can develop to their full potential.

TRUST
We trust each other, we are transparent and we empower people. We respect diversity.

INTEGRITY
We act in the interest of ENTSO-E

TEAM
We care about people. We work transversal and we support each other. We celebrate success.

FUTURE THINKING
We are a learning organisation. We explore new paths and solutions.

We are ENTSO-E