Control Center Interfaces and Tools for Power System Restoration

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Summary / Abstract

The electricity system is operated more frequently closer to its security limits. This leads to higher risks of emergency and blackout situations. In case of a blackout, grid operators are in charge of a fast and secure grid restoration. The restoration includes the communication and interactions between all involved parties. Based on different blackout states and power system restoration strategies, a new control center interface for communication tasks and interactions during grid restoration is introduced. Furthermore, associated restoration tools are developed to relieve and support the grid operators. The interfaces and tools are tested for a blackout situation in Austria using an operator-training simulator.

1 Introduction

The nuclear phase-out, increasing infeed of renewable energy sources (RES), large-scale energy trading and delayed grid enhancements lead to system operation closer to security limits. To ensure system security, grid operators in Germany had to intervene with redispatch measures of 20,438 GWh and reduction of renewable infeed of 5,518 GWh in 2017, which is an all-time high [1]. These continuously expanding challenges in grid operation increase the risk of emergency situations or even blackouts. In case of a blackout, the automatic reconnection of RES endangers the restoration process since small islands are very sensitive to power imbalances. Along with the increased cold-load-pick-up due to electric vehicles and heat-pumps the grid operators face additional challenges [2].

To support grid operators in such a crucial situation, control center tools specially designed for power system restoration are proposed to improve the awareness of the own system and to provide decision support [3]. Beyond that, a fast and secure power system restoration requires an intense cooperation and coordination between all responsible system operators (SOs), power plant operators (PPOs), especially PPOs that provide restoration services, and significant grid users (SGUs). In Germany there are 888 distribution system operators (DSOs) [4] subordinate to four transmission system operators (TSOs), whereas in Austria there are 121 DSOs [5] subordinate to two TSOs.

The large number of parties involved causes a high complexity and communication demand for the operators. First awareness systems are in place, e.g. the ENTSO-E Awareness System improves the TSO's awareness of other parts of the European network but is not specifically designed for power system restoration and covers only TSOs [6]. The Austrian Awareness System is a regional system for information exchange and communication in emergency and restoration conditions between the Austrian's TSOs and DSOs [7].

This paper proposes standardized interfaces between control centers to reduce the communication and coordination tasks of grid operators, which are today still mostly done via telephone. Figure 1 shows the framework of the interfaces and the restoration tools.

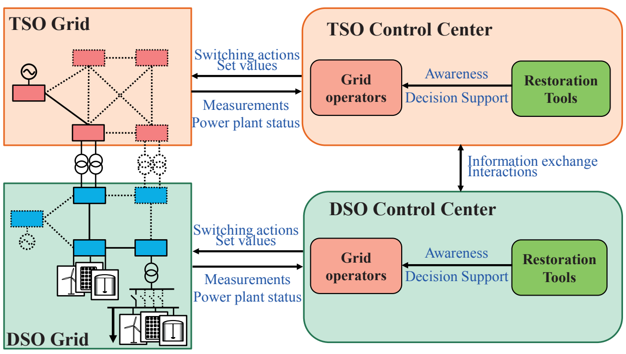

Figure 1 Framework of the restoration tools

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The framework includes schemes about how such supporting tools between all different SOs shall interact and which system information should be exchanged.
Besides increasing the awareness of the neighboring system states, the tool provides decision support for interactions between neighboring SOs such as voltage forwarding, re-synchronization and meshing of already synchronized grids. The restoration tools are capable to support a partially autonomous grid operation.

2 Power system restoration

2.1 Strategies

In case of a blackout state of the power system, TSOs are responsible for a fast and secure re-energization of consumers. To achieve this goal, different restoration strategies and plans have been developed. The network code on electricity emergency and restoration distinguishes between two restoration strategies. The top-down re-energization strategy uses an external voltage source from tie lines of neighboring TSOs to re-energize the system. Within the bottom-up strategy, the TSO uses own black start- and island-capable power plants [8]. These two strategies only consider the coordinated actions and relationships between TSOs. Therefore, [9] enhances the restoration strategies defined in the network code and includes the different roles and responsibilities of TSOs and DSOs.
Within the build-down strategy, the DSO uses no black start unit and requires the assistance of the upstream TSO; within the build together strategy both TSO and DSO are self-energized separately; within the build-up strategy the DSO is self-energized and forwards voltage to the TSO whose black start capability is not available.
According to the Austrian law in § 40 Section 1 Sentence 15 ElWOG 2010, the TSOs are solely responsible for the power system restoration. Due to the special generation structure in Austrian distribution grids with high amounts of hydro power, a build-together strategy was developed [10]. It includes the DSOs as active and independent partners in the power system restoration process. In the distribution grids of KNG-Kärnten Netz GmbH and Netz Oberösterreich GmbH, black start and island capable hydro power plants are available from which the restoration process would start on a regional level. This coordinated approach accelerates the power system restoration and provides a back-up solution in case TSOs cannot provide voltage in a timely manner [11], [12].

2.2 Blackout and restoration states, roles and responsibilities

In order to determine the necessary information exchange between the control centers and possible interactions between the SOs, it is necessary to generalize further the different blackout and restoration states as well as the corresponding roles and responsibilities. The generalization refers to the point of view of one SO.

In principle two blackout condition categories for a SO are possible: either a complete blackout, where the entire power system of the particular entity is de-energized, or a partial blackout, where parts of the system are de-energized and other parts are still energized forming one or more islands. Starting from these two blackout states, different state changes are possible, see Figure 2.

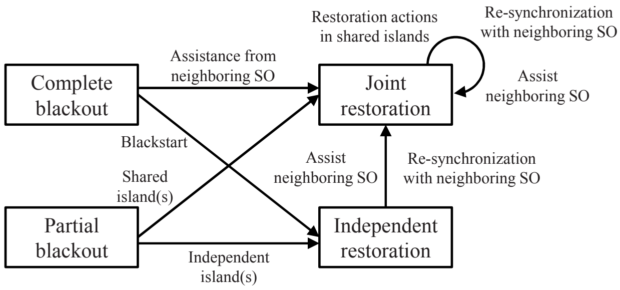

Figure 2 Blackout and restoration states

In case of a complete blackout, the power system restoration can be either started by using own black start and island capable power plants or by assistance of a neighboring SO, who provides voltage to re-energize the disturbed system. This leads in the first case into an independent restoration or in the second case into a joint restoration.
In case of a partial blackout, the remaining islands could be shared with different SOs, which leads into a joint restoration, or the remaining islands could be independent from other SOs, which leads into an independent restoration.
During the independent restoration state, the SO is responsible for its island(s) and should provide appropriate information to neighboring SOs about the island(s) and the restoration progress. Note, that the independent restoration state is only an intermediate state to a joint restoration where the transition is either possible by assisting neighboring SOs or by re-synchronization with neighboring SOs.
During the joint restoration, coordinated restoration actions between all involved SOs are necessary. One SO is the frequency leader and gives specifications about active power exchange and maximum allowed active power steps to all SOs. With re-synchronization with neighboring SOs or assistance to neighboring SOs, the restoration process continues building a more and more stable grid with the final goal to achieve again a synchronized grid in Continental Europe.
Looking at the Austrian build-together restoration strategy for a complete blackout scenario, DSOs and TSOs start their own black start units and every SO is in the independent restoration state responsible for the respective islands. After the re-synchronization between DSOs and TSOs, the TSOs will take the role of the frequency leader in the joint restoration of the shared island. The DSOs then have to follow the TSO's instructions and follow the specified active power exchange. DSOs with high shares of generation could also provide active power flexibilities to the TSOs.

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3 Tool interfaces

3.1 Interactions

During the power system restoration, coordinated restoration actions between the SOs are required. Figure 2 shows the possible interactions between SOs as state changes, which end in the joint restoration: restoration actions in shared islands, re-synchronization with neighboring SOs and assistance of neighboring SOs. The interactions depend on the own grid status and on the grid status of the neighboring SO. There are basically four alternatives: i) grids of both SOs are (partly) energized and share the same island, ii) grids of both SOs are (partly) energized but are part of different islands, iii) a grid of only one SO is (partly) energized and iv) grids of both SOs are not energized yet.

In case i), coordinated restoration actions in shared islands are necessary. The frequency leader can specify active power exchange values and maximum tolerable load pick-ups to neighboring SOs. SOs in the shared islands can ask for a change of their active power exchange values either to reconnect load or to provide active power flexibilities by controllable power sources. A change of active power exchange values has to be approved by the neighboring SO. In addition, neighboring SOs can further mesh their power systems.

In case ii), a re-synchronization with neighboring SOs is possible. Therefore, the re-synchronization point, the re-synchronization leader and the frequency leader of the newly shared island have to be specified. Afterwards the interactions are according to case i).

In case iii), the SO having a stable island can assist neighboring SOs by providing voltage to the interconnector. From this point, the neighboring SO can start its restoration, e.g. by using external starting grids. Afterwards the interactions are according to case i).

In case iv), no interactions are possible yet.

3.2 Information exchange

Based on the preliminary considerations of the power system restoration process, the following information should be exchanged between the control centers. They reflect the roles, responsibilities and possible interactions.

Every SO should send them to its neighbors: the grid status, number of islands, and the reconnected load in percent of total load. For every island, the SO should send to its neighbors:

- grid frequency,
- frequency stability indicators,
- grid operators which are part of the island (if applicable),
- frequency leader,
- equivalent model (e.g. short-circuit power),
- load and load forecast,
- information about non-controllable renewable generation (total installed power of synchronized generation, actual infeed and forecast),
- information about controllable renewable generation (total installed power of synchronized generation , actual infeed and forecast),
- information about conventional power plants (total installed power of already synchronized power plants and actual infeed),
- indicator whether the island is ready for being re-synchronized or time frame until the island is ready for being re-synchronized.

Each interaction can be sent by a SO and the corresponding SO can confirm or reject the request. Table I shows the necessary information exchange for restoration interactions.

Table I Information exchange for restoration interactions

Case	Restoration Interactions	Exchanged Information
i) Shared Island	Meshing of power system with neighboring SO	• Path for meshing the grids • Meshing point • Status of the meshing process
	Specification of active power ex-change values	• Active power exchange values
	Specification of maximum tolerable cold load pick-up	• Maximum tolerable cold load pick-up
ii) Independent islands	Re-synchronization with neighboring SO	• Re-synchronization path • Re-synchronization point • Re-synchronization leader • Status of re-synchronization process • Frequency leader of the newly shared island • Active power exchange values • Maximum tolerable load pick-up
iii) Only own grid partly energized	Assist neighboring SO	• Interconnector where the voltage is forwarded • Active power exchange values • Maximum tolerable load pick-up

4 Restoration Tools

4.1 Awareness Tool for neighboring system operators

The Awareness Tool for neighboring systems visualizes, beyond the capability of currently existing control center tools, the most important system information of neighboring power systems, which are received according to the described information exchange in section 3.2. This includes general information of SOs' grid status and information about each island of the neighboring SOs. This overview improves the system awareness of the restoration progress of neighboring SOs.

Each SO in the shared island has an information field of the actual active power exchange values and maximum tolerable load pick-up as well as a field where the SO can ask for a value change.

4.2 Decision Support Tool for interactions with neighboring system operators

4.2.1 Meshing of power system with neighboring SO

For meshing with the neighboring SO, the Decision Support Tool determines all shortest paths from all energized nodes of one SO to the neighboring SO. The tool evaluates the paths according to their influence on the system's voltage and reactive power reserves. The tool also checks the maximum allowed voltage and angle difference when the mesh is closed. The best path is then proposed to the SOs.

4.2.2 Re-synchronization with neighboring SO

For re-synchronization with the neighboring SO, the Decision Support Tool calculates all shortest paths from all energized nodes of one SO to the neighboring SO. The tool evaluates the paths according to their influence on the system's voltage and reactive power reserves. The tool chooses for the re-synchronization a substation with a synchronizing devices and checks the maximum allowed voltage and frequency differences. The best path is then proposed to the SOs.
The SO having the highest amount of synchronized installed power plant capacity in its island is chosen first as re-synchronization leader and afterwards as frequency leader.

4.2.3 Assist neighboring SO

For assisting neighboring SOs, the Decision Support Tools on both sides calculate the path for voltage forwarding. The results are exchanged between the respective Decision Support Tool.

5 Simulations

5.1 Grid models and simulation environment

The tool interfaces are tested using grid models of Austrian Power Grid AG (APG), KNG-Kärnten Netz GmbH (KNG) and Netz Oberösterreich GmbH (NOÖ) representing a future scenario 2025 with high shares of renewable generation. This grid model of one TSO and two DSOs allows the test and verification of the above described information exchange and interactions.
Figure 3 shows the simulation environment of the restoration tools. Three work places are set up, each one representing one control center. The according grid models are implemented into DUtrain's Power System Handler (PSH). The PSH is a real time dynamic operator-training simulator, whose purpose is to train grid operators in a realistic control center replica [13]. Every 10 seconds the PSH outputs the power flow results, a high-resolution frequency and the status of all power plants of each SO. This data is used as input for the restoration tools in MATLAB-MATPOWER [14]. The restoration tools exchange all necessary information for the awareness and decision support functionalities via data containers in 1 second time steps. Via two graphical user interfaces in MATLAB, one for awareness- and one for decision-support-functionalities, the restoration tools interact with the operators. The restoration tools then send the commands chosen by the operator to the PSH.

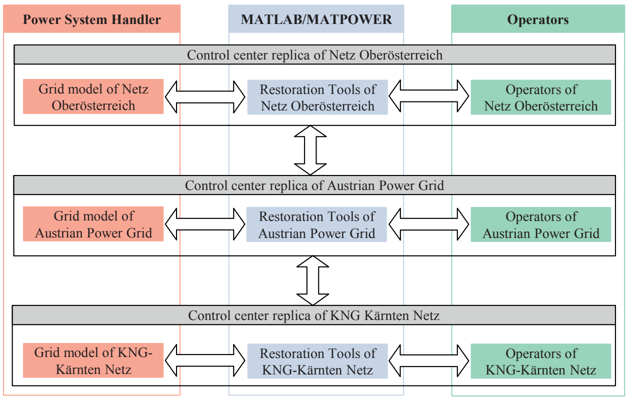

Figure 3 Simulation environment

5.2 Test cases and results

For a test scenario, a restoration case is created and the restoration is started by KNG from the pumped hydro power plant in substation *Innerfragant* with three generators having a total installed power of 102 MW. In APG, the restoration is started from the pumped hydro power plant in substation *Kaprun* with four generators with a total installed power of 480 MW. From substation, *Kaprun* a starting grid leads to substation *Vienna*, as seen in Figure 4 (PSH screenshots).
The information according to section 3.2 is exchanged between KNG and APG and the Awareness Tool visualizes this information, see Figure 5. On the left, the Awareness Tool of KNG shows information about the APG-island and, on the right, the Awareness Tool of APG shows information about the KNG-island. KNG already reconnected 20 MW of loads, which are mixed with 5 MW renewable infeed. Both SOs are ready for re-synchronization.
The Decision Support Tool calculates 28 different re-synchronization paths and the best path according to the system's voltages and reactive power reserves is proposed to the operators, see Figure 6.

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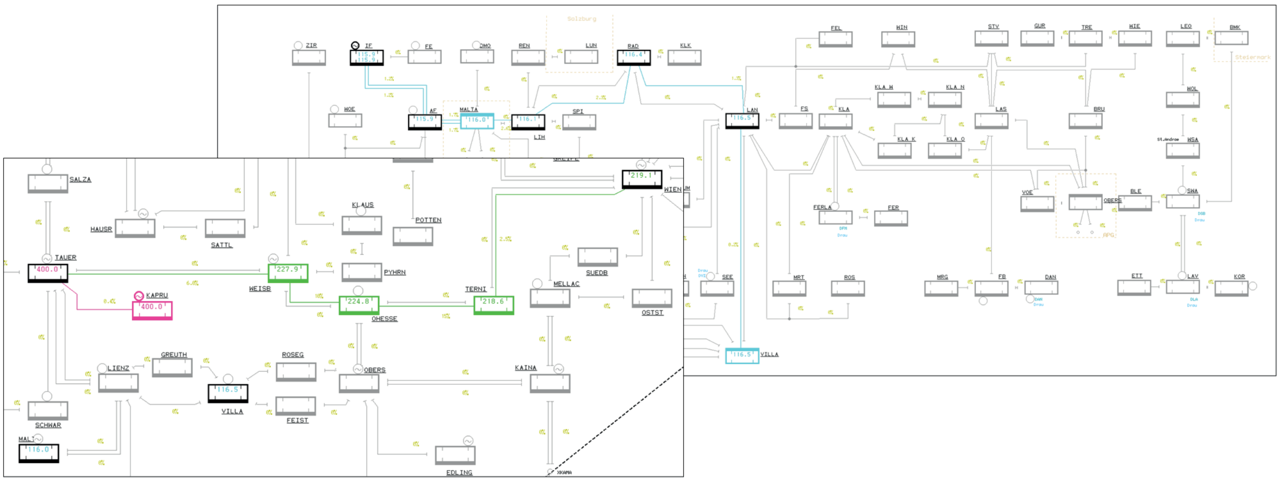

Figure 4 PSH initial screenshots of APG (left) and KNG (right)

Austrian Power Grid

Grid status: Restoration
Number of islands: 1
Reconnected loads: 0.2 % (of LFC area)

Island 1
Frequency leader: APG
System operators in islands: APG
Grid frequency: 50.01 Hz
Dynamic frequency stability: 37 MW/Hz
Ready for re-sychronization: Yes

	P_r	P_{act}	P_{act+1h}
Conv. power plants:	480 MW	0 MW	----
Load:	----	----	----
Non controll. RES:	----	----	----
Controllable RES:	----	----	----

KNG-Kärnten Netz

Grid status: Restoration
Number of islands: 1
Reconnected loads: 0.5 %

Island 1
Frequency leader: KNG
System operators in islands: KNG
Grid frequency: 50.00 Hz
Dynamic frequency stability: 11 MW/Hz
Ready for re-sychronization: Yes

	P_r	P_{act}	P_{act+1h}
Conv. power plants:	102 MW	15 MW	----
Load:	----	20 MW	22 MW
Non controll. RES:	8 MW	5 MW	7 MW
Controllable RES:	----	----	----

Figure 5 Awareness Tool before re-synchronization

Path-Information

Re-Synchronization Point: Malta 110 kV
Minimum voltage on path (110 kV): 116.0 kV
Maximum voltage on path (110 kV): 116.0 kV
Minimum voltage on path (220 kV): 231.4 kV
Maximum voltage on path (220 kV): 232.6 kV
Minimum voltage on path (380 kV): 400.5 kV
Maximum voltage on path (380 kV): 402.9 kV
Max. allowed voltage difference: 15 kV
Calculated voltage difference: 1.7 kV
Max. allowed frequency difference: 0.25 Hz
Frequency difference: 0.01 Hz

Path equipment

SO	Nr	Element	Substation 1	Substation 2	Un (kV)		
APG	1	Line	Tauer	Lienz	380	Select	Execute
APG	2	Transformer	Tauer	---	380-220	Select	Execute
APG	3	Line	Lienz	Malta	220	Select	Execute
APG	4	Transformer	Malta	---	220-110	Select	Synchronize

Figure 6 Proposal for the re-synchronization path

Since APG has the more stable grid, APG is the re-synchronization leader and, after the re-synchronization, APG is frequency leader of the shared island. Figure 8 shows a PSH screenshot of APG and KNG after the re-synchronization. The re-synchronization path is highlighted in bold green and margenta. Now, APG can specify the active power exchange and maximum tolerable load pick-up for KNG. APG specifies the active power exchange between 0 and 50 MW and the maximum tolerable load pick-up to 5 MW. Since APG and KNG are just connected via one transformer, a meshing of the two grids is advisable, see the mesh proposal of the Decision Support Tool in Figure 7. The path for meshing the grids is highlighted in bold gray in Figure 8.

Path-Information

Closing Point of mesh : Villa 110 kV
Minimum voltage on path (110 kV): 116.7 kV
Maximum voltage on path (110 kV): 118.2 kV
Minimum voltage on path (220 kV): 233.0 kV
Maximum voltage on path (220 kV): 235.3 kV
Minimum voltage on path (380 kV): -----
Maximum voltage on path (380 kV): ----
Max. allowed voltage difference: 15 kV
Calculated voltage difference: 0.1 kV
Max. allowed angle difference: 15°
Angle difference: 0.4°

Path equipment

SO	Nr	Element	Substation 1	Substation 2	Un (kV)		
APG	1	Line	Ohesse	Obers	220	Select	Execute
APG	2	Transformers	Obers	-----	220-110	Select	Execute
KNG	3	Line	Obers	KLA	110	Select	Execute
KNG	4	Line	KLA	LAN	110	Select	Close mesh

Figure 7 Proposal of the path for meshing the grids of KNG and APG

6 Conclusion and outlook

The restoration tool interfaces significantly reduce the communication tasks of grid operators and support them in their decision-making process. The decision support ensures a high level of security and speeds up the restoration process. Especially in cases where pre-defined restoration strategies between grid operators cannot be applied, restoration tools can provide alternative procedures.

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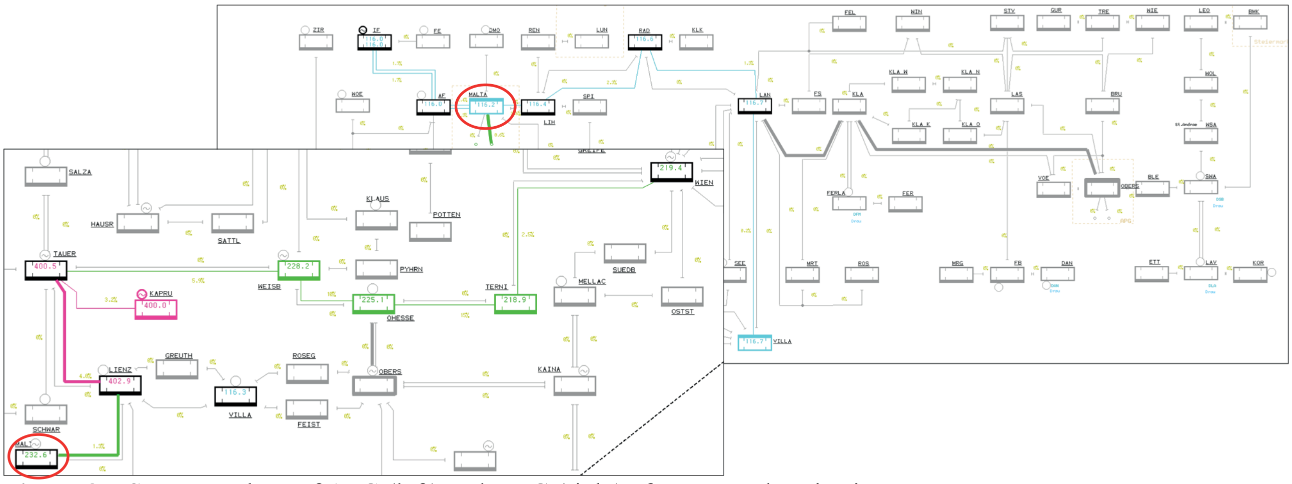

Figure 8 PSH screenshots of APG (left) and KNG (right) after re-synchronization

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