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Strategies and Operator Tools for Grid Restoration with Massive Renewable Energy Sources

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Strategies and Operator Tools for Grid Restoration with Massive Renewable Energy Sources

RestoreGrid4RES

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Ein Projektbericht im Rahmen des Programms

STADT der Zukunft

des Bundesministeriums für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (BMK)

Vorbemerkung

Der vorliegende Bericht dokumentiert die Ergebnisse eines Projekts im Rahmen der „Joint Programming Platform Smart Energy Systems“ (JPP SES) - ehemals ERA-Net Smart Grids Plus. JPP SES ist ein Netzwerk nationaler und regionaler Förderprogramme mit dem Ziel, die Erforschung, technische Entwicklung und Demonstration von zukunftsweisenden Lösungen für intelligente, integrierte Energiesystemen voranzutreiben.

Die transnationale Programminitiative mit über 30 nationalen und regionalen Förderpartnern aus 25 Ländern bietet eine nachhaltige und dienstleistungsorientierte gemeinsame Programmplattform zur Finanzierung von transnationalen FTI-Projekten, die Technologien und Lösungen in Themenbereichen wie Smart Grids, regionale und lokale Energiesysteme, Wärme- und Kältenetze und intelligente Dienstleistungen entwickeln. Das Ziel ist die Initiierung von Co-Creation-Prozessen und Förderung von Energiesysteminnovationen. Darüber hinaus bietet JPP SES eine Wissensgemeinschaft, die wichtige Demonstrationsprojekte und Expert:innen aus ganz Europa einbezieht, um das projekt- und programmübergreifende Lernen von der lokalen bis zur europäischen Ebene zu erleichtern.

Österreich beteiligt sich aktiv mit Forschungsbeiträgen in den Bereichen Smart Grids und integrierte regionale Energiesysteme. Für die Österreichische Energieforschung ergeben sich durch die Beteiligung an der Forschungsinitiative der JPP SES viele Vorteile: Viele Entwicklungen können durch internationale Kooperationen effizienter bearbeitet werden, neue Arbeitsbereiche können mit internationaler Unterstützung aufgebaut sowie internationale Entwicklungen rascher und besser wahrgenommen werden.

Dank des überdurchschnittlichen Engagements der beteiligten Forschungseinrichtungen ist Österreich erfolgreich in der JPP SES verankert. Durch zahlreiche JPP SES Projekte entstanden bereits wertvolle Inputs für europäische und nationale Energieinnovationen und auch in der Marktumsetzung konnten bereits richtungsweisende Ergebnisse erzielt werden.

Die Initiative wird vom Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (BMK) mit Unterstützung der Österreichischen Forschungsförderungsgesellschaft (FFG) koordiniert.

Ein wichtiges Anliegen des Programms ist es, die Projektergebnisse durch diese Publikationsreihe und über nachhaltigwirtschaften.at einer interessierten Fachöffentlichkeit zugänglich zu machen.

DI Theodor Zillner
Interimistischer Leiter der Abt. Energie- und Umwelttechnologien
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1 Kurzfassung

Der steigende Anteil fluktuierender erneuerbarer Energien im Stromsystem und die Liberalisierung des Strommarktes führen zu einer erhöhten Systembeanspruchung bezüglich Netzauslastung und Fluktuation. Kombiniert mit den Verzögerungen beim Netzausbau ergeben sich somit steigende Risiken für großflächige Stromausfälle und Bedrohungen für den erfolgreichen Netzwiederaufbau. Ziel dieses Projekt war es, neue Netzwiederaufbaustrategien zu entwickeln, um einen schnellen, koordinierten und stabilen Systemwiederaufbau zu gewährleisten. Insbesondere sollten Empfehlungen ermittelt werden, ob und wie erneuerbare Energietechnologien zum Netzwiederaufbau beitragen können, und hierfür notwendige technische Anforderungen identifiziert werden, unter Berücksichtigung des Umstands, dass erneuerbare Energietechnologien oftmals auf Verteilnetzebene angeschlossen sind – ohne direkte Zugriffsmöglichkeit seitens des Übertragungsnetzbetreibers. Es wurde ein Demonstrationsmodell entwickelt, das Netzbetreibern im Netzwiederaufbauprozess unterstützt und hierbei hilfreiche Informationen über mögliche nächste Schritte und deren Folgen liefert.

RestoreGrid4RES behandelt die zukünftige Erzeugungsstruktur auf Basis erneuerbarer Einspeiser im Zuge der Transformation auf eine erneuerbare und ökologische Stromversorgung. Neben der Bewältigung eines hohen Anteils von Erneuerbaren im normalen Netzbetrieb, hat sich auch der Netzbetrieb in Notsituationen mit dieser Entwicklung zu befassen. Im unwahrscheinlichen Fall eines systemweiten Blackouts, müssen Netzwiederaufbaustrategien zur Verfügung stehen, welche definieren, wie der Netzwiederaufbau geordnet ablaufen soll. Das Ziel des Projekts war daher der sichere Netzwiederaufbau nach einem systemweiten Blackout in Stromnetzen mit hohem Anteil erneuerbarer Energien.

Zur Zielerreichung waren zwei Kernelemente des Projekts essentiell: Erstens galt es, neue Netzwiederaufbaustrategien zu entwickeln und Lösungen aufzeigen, wie Netzwiederaufbau ohne Störung durch dezentrale erneuerbare Energietechnologien gewährleistet werden kann. Hierbei wurde unter anderem auch das veränderte Netzverhalten bei der Kaltlastaufnahme berücksichtigt. Darüber hinaus wurde untersucht, wie erneuerbare Energietechnologien aktive Beiträge zum Netzwiederaufbau leisten können und welche Netzdienstleistungen sie erbringen bzw. Anforderungen hierfür erfüllen müssen. Zweitens wurden im Rahmen des Projekts innovative, aber auch gleichzeitig robuste, vertrauenswürdige und sichere Operator-Tools entwickelt, welche ein Minimum an Inputdaten benötigen und die Netzbetreiber beim Wiederaufbau aktiv unterstützen und durch zielgerichtete Informationsbereitstellung zu möglichen nächsten Schritten und deren Folgen begleiten.

Die österreichischen Partner in diesem Projekt waren in allen Arbeitspaketen involviert und arbeiteten insbesondere an folgenden Themen:

- Als erster Schritt wurde eine Bestandsaufnahme der bestehenden Praxis punkto Systemwiederaufbauverfahren unter Berücksichtigung der gesetzlichen Rahmenbedingungen und technischen Anforderungen durchgeführt. Basierend auf der langjährigen Erfahrung der im Projekt beteiligten österreichischen Netzbetreiber galt es, hierbei auch die Grenzen und Ergänzungsmöglichkeiten derzeitiger Regelungen zu identifizieren.
- Modelle für quasistationäre Betrachtungen erneuerbarer Energietechnologien wurden entwickelt, um die Einflüsse der erneuerbaren Erzeugung auf den Netzwiederaufbau zu

analysieren. Hier lag der Schwerpunkt österreichischer Projektpartner bei Modellen von Kleinwasserkraftwerken sowie den Erfahrungen über weitere erneuerbare Energien wie PV und Windkraft sowie auch Speicher und Lastmodelle.

- Neue Netzwiederaufbaustrategien wurden unter Berücksichtigung der Erfahrungen der österreichischen Projektpartner und Interessensgruppen entwickelt. Hierbei wurden unterschiedliche Ansätze (d.h. Top-Down, Bottom-Up oder deren Kombination) berücksichtigt und unter Anwendung der zuvor entwickelten Modelle sowohl der Einfluss erneuerbarer Energietechnologien als auch ihre mögliche proaktive Verwendung untersucht.
- Schließlich wurden Empfehlungen und ein Fahrplan für den Systemwiederaufbau abgeleitet, welche von österreichischen Netzbetreibern genutzt werden können.

Die entwickelten Wiederaufbaustrategien unter Berücksichtigung der eventuell aktiven Nutzung erneuerbarer und dezentraler Erzeugung führten auch zu Empfehlungen für eine Neugestaltung der Netzanschlussregeln hinsichtlich Netzdienstleistungen. Diese Netzdienstleitungen sind essentiell, damit diese Technologien erfolgreich zum Gesamtsystemwiederaufbau beitragen können. Während viele Smart-Grid-Projekte sich auf regionale Smart Grids konzentrieren, berücksichtigte dieses Projekt das gesamte mitteleuropäische Übertragungssystem, in dem Österreich ein integrativer Bestandteil ist. Des Weiteren wurde eine transparente Übersicht bestehender Netzwiederaufbaustrategien erarbeitet, um abzuschätzen, ob diese Strategien im veränderten Netzsystem mit wachsendem Anteil erneuerbarer und dezentraler Erzeugung angemessen sind.

2 Abstract

The growing contribution of renewable energies and the liberalisation process in electricity markets result in higher system stresses in terms of increasing system loadings and fluctuations. Combined with a delay of grid enhancements this results in an increasing risk of wide-area blackouts and a threat for successful grid restoration. This project investigated new grid restoration strategies to ensure a fast, coordinated and stable system restoration. In particular, on the one hand, it gives recommendations whether and how renewable generators shall contribute to the restoration process and, on the other hand, it identifies technical requirements that must be met observing the fact that the vast majority of renewable generation is connected to the distribution systems without direct control by the transmission system operators (TSO). To support the operators during this difficult procedure, a demonstration tool has been developed which shall guide the operators through the restoration process and give helpful information about possible next steps and their consequences.

RestoreGrid4RES faces the future renewable based generation structure within the transformation to a renewable and ecological power supply. Besides coping with a high share of renewable energies in normal grid operation, grid operation in emergency situations has to deal with this progression as well. In the unlikely event of a system-wide blackout, there have to be restoration strategies available which define how to restore the electricity system. This determined the aim of the project which is to ensure a fast but secure grid restoration after a system wide blackout in networks with high renewable energy generation.

Therefore, two main targets had to be achieved. First, by taking into account the modified cold load pick-up behaviour of networks including distributed generation, new grid restoration strategies have been developed to answer the question how grid restoration can proceed without interference by distributed renewable energy technologies. Moreover, it has been examined how renewable energy technologies may be actively used in the restoration process and what ancillary services or requirements they have to fulfil. Second, because of the need for new, trustworthy, robust and secure operator tools, an innovative restoration tool has been developed to guide the operators during grid restoration and to provide information about possible next steps and their consequences.

The Austrian partners played an important role in this project and have been involved in all work packages. Specifically, they have worked on following topics:

- As a first step, a review of current practices for a system restoration process has been conducted – with consideration of the legal framework and technical requirements. Thereby, also limitations of current practices have been identified - based on the vast experience of Austrian distributed system operators involved in the project.
- Steady state models of renewable energy technologies have been developed that allow for analysing the influence of renewable generation on grid restoration. Here, the focus of Austrian project partners was on models of small hydro generation typically in place in Austria, but also leveraging on knowledge about other renewable generation like photovoltaic and wind power plus storage and load models.
- New grid restoration strategies, in particular top-down, bottom-up or a combination of both approaches have been developed under consideration of lessons learned from Austrian

stakeholders and project partners. In this context, by use of the previously developed models, the influence of renewable energy technologies as well as their possible proactive use has been examined. Derived strategies have been optimized based on quantification of economic costs and social welfare impacts.

- Finally, based on previous outcomes, recommendations and a roadmap for migration towards the proposed system restoration plan have been derived, which can be used by other Austrian system operators as well.

The developed restoration strategies with specific consideration of possibly active use of renewable and distributed generation result in recommendations on grid codes for emergency and restoration with respect to the ancillary services that these generators have to provide to successfully contribute in the overall system restoration process. While many smart grid projects focus on small smart grids (Microgrids), this project takes the whole Central European transmission system, of which the Austrian system is an integrative part, into account and thus gains a high scaling up-potential. The project provided a transparent overview of current grid restoration approaches. Thereby, it enables an assessment of the suitability of these approaches in the changing environment by increased installation of distributed energy resources. Thus, it allows a gap analysis and identification of necessary steps for Austrian system operators to adapt these approaches under new system conditions.

3 Initial situation

RestoreGrid4RES faces the future renewable based generation structure within the transformation to a renewable and ecological power supply. Besides coping with a high share of renewable energies in normal grid operation, grid operation in emergency situations has to deal with this progression as well. In the unlikely event of a system-wide blackout, there have to be restoration strategies available, which define how to restore the electricity system. This determines the aim of the project, which is to ensure a fast but secure grid restoration after a system wide blackout in networks with high renewable energy generation.

3.1. Main project goals

First, new grid restoration strategies have to be developed answering the question how grid restoration can proceed without interference by renewable energy sources taking into account the modified cold load pick-up behaviour of networks including distributed generation. Beyond that, it is examined how renewable energy sources may be actively used in the restoration process and what ancillary services or requirements they have to fulfil. Second, new trustworthy, robust and secure operator tools have to be developed which help the operators in particular during grid restoration with useful information but require little input data. This proposed innovative tool guides the operator during grid restoration by providing both awareness about the system status and current flexibility options and decision support about possible next steps and their consequences.

RestoreGrid4RES is a joint project of the University of Kaiserslautern, TU Wien, KNG-Kärnten Netz GmbH, Netz Oberösterreich (NOÖ) GmbH, and Siemens AG. Developing restoration strategies requires a scientific approach as well as practical hands-on experience. For this reason, a combined effort of research institutes and industrial partners creates ideal framework conditions. The participating organizations are listed in Table 1.

The final report has been arranged by the Vienna University of Technology (TUW), Institute of Energy Systems and Electrical Drives. The TUW has participated in all work packages and had a lead in WP2 and WP4 and part of WP6. The tasks in these work packages have been mainly handled by TUW to find an optimization algorithm for the simulation of the restoration process and to develop new strategies concerning RES in the network. The project members of Technische Universität Kaiserslautern (TUKL) have participated in all work packages. The tasks in WP3, WP5 and part of WP6 have mainly been performed by TUKL. The project members of KNG-Kärnten Netz GmbH have extensive expertise and wide experience in the energy sector, in operation management and outage clearance in distribution systems as well as in the integration of renewables in medium and low voltage grids. The project members are experts in grid restoration strategies and have experience regarding grid restoration tests and in this context the development of dynamic grid models. The members of Netz OÖ as a subsidiary of Energie AG have provided experience and Know-how in the field of smart metering, network integration of photovoltaic systems and voltage control solutions. Netz Oberösterreich participates following the aim to develop solutions to be successfully put into practice and further deployed in certain parts of the area.

	Name	Partner type	Address	Contact name	Contact email
Lead partner	TU Kaisers-lautern	Public research organisation	Erwin-Schroedinger-Straße, Building 11, 67663 Kaiserslautern, Germany	Prof. Dr.-Ing. Wolfram Wellssow	wellssow@eit.uni-kl.de
Project partner	TU Wien	Public research organisation	Gußhausstraße 25/370-1, 1040 Wien, Austria	Prof. Dr.-Ing. Wolfgang Gawlik	wolfgang.gawlik@tuwien.ac.at
Project partner	KNG-Kärnten Netz GmbH	Private - SME	Arnulfplatz 2, 9020 Klagenfurt am Wörthersee, Austria	Priv.-Doz. Dipl.-Ing. Dr.-techn. Robert Schmaranz	robert.schmaranz@kaerntennetz.at
Project partner	Netz Oberöster-reich GmbH	Private - SME	Neubauzeile 99, 4030 Linz, Austria	Ewald Traxler	ewald.traxler@netzgmbh.at
Project partner	Siemens AG, EM SG PTI	Private – Large company	Freyeslebenstr. 1, 91058 Erlangen, Germany	Prof. Dr.-Ing. Rainer Krebs	rainer.krebs@siemens.com

Table 1: Participating organizations in project RestoreGrid4RES

3.2. Current situation

The current situation of the system Average Interruption Duration Index SAIDI is depicted in Figure 1.

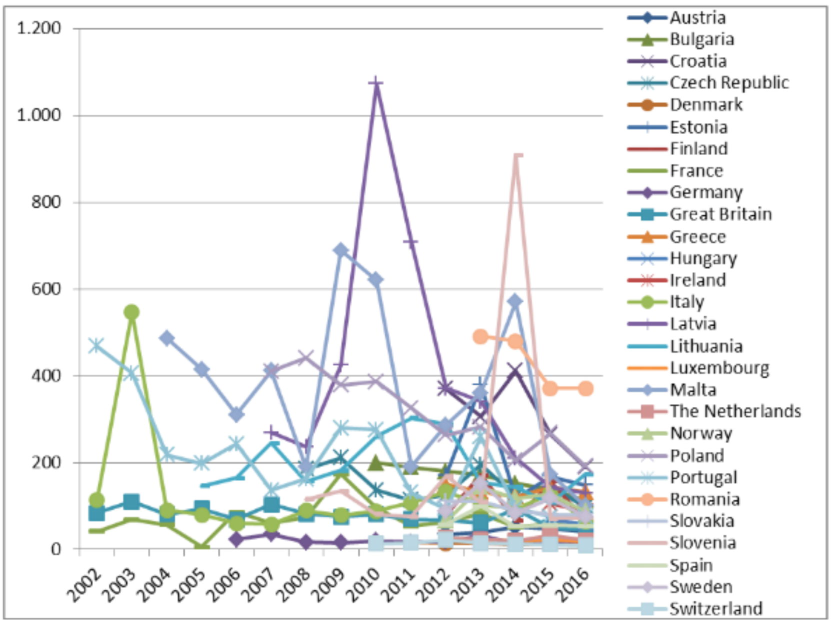

Figure 1: Electricity: Unplanned SAIDI, including exceptional events (minutes per customer)[1]

The SAIDI is the behaviour of the sum of all customer interruption durations to the total number of customers served.

[1] https://www.ceer.eu/

The values presented show variations due to extreme weather situations of the past years but tend to stabilise in the years 2015 and 2016 with the highest value just under 400 minutes per customer per year. The SAIDI values according to E-Control in Austria are depicted in Figure 2. The bar values show the SAIDI without natural disasters and the blue line shows the values with natural disasters.

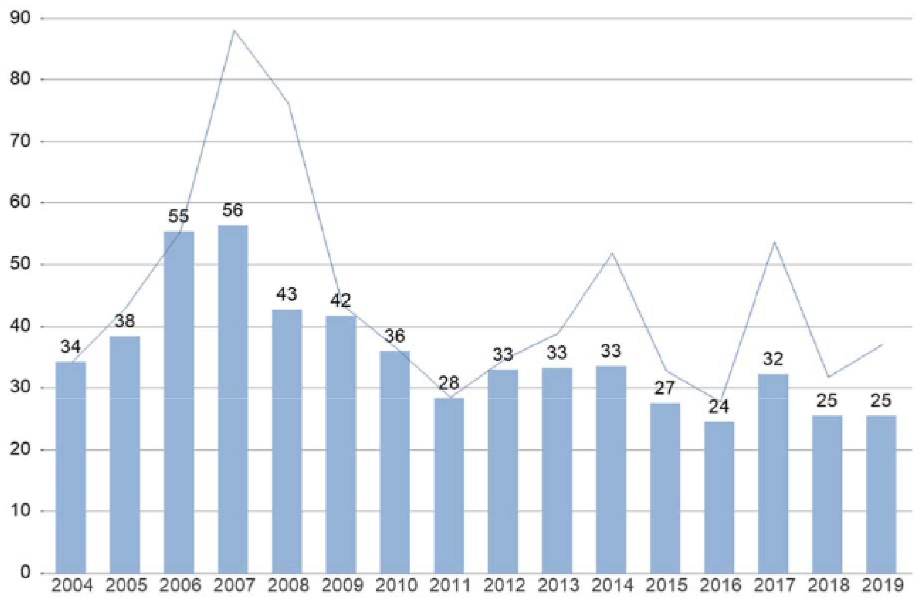

Figure 2: Electricity: Unplanned SAIDI in Austria[2]

System operator requirements are defined in the following section:

According to § 11 section 1 EnWG: "System operators are obligated to maintain a reliable and efficient energy supply without discriminatory insofar as it is economically reasonable. In particular, they have to fulfil the tasks according to §§12 to 16a. The obligation is applied in the context of exercising of the power of economic management of the vertically integrated system operators and his regulatory law according to the § 7a section 4 sentence 3 [**Fehler! Verweisquelle konnte nicht gefunden werden.**].

According to the ENTSO-E network code, there exist two possible PSR strategies, namely top-down and bottom-up, or a combination of these two strategies. Combinations of these two strategies are possible. In this manner, the assistance of other TSOs as well as BSU capable power plants available in the TSO control area are used to re-energize the power system. If it is feasible for these TSOs to assist during the re-energization, this strategy should be utilized and TSOs should connect the needed amount of power load demand. On the other hand, in case the neighbouring TSOs would enter into an emergency or a blackout state when providing assistance, the bottom-up strategy should be used instead. In this strategy, no assistance from other TSOs is received and BSU capable power plants are available for self-re-energization. Combinations of both, top-down and bottom-up strategies, are also possible. The ENTSO-E network code only describes the relationship and possible actions between TSOs in case of a PSR state. The responsibility of DSOs is not addressed [2].

During system restoration, high shares of distributed generation (DG), often in the form of renewable energy sources (RES) with automatic synchronization characteristics, may lead to system instability and an increased risk of a second blackout. In addition, the peak value of loads after an interruption

[2] https://www.e-control.at

can be significantly higher than at normal operation, which causes additional challenges. This is known as cold load pick-up (CLPU) [3].

3.3. Method to achieve the goals

As a first step, current practices for a system restoration process following a wide-area blackout were reviewed with consideration of the legal framework and technical requirements. Also, limitations of the current system were identified.

To study the impact of renewable generation during grid restoration, quasi steady-state models of renewable energy sources were developed which require limited input data. Also, storage facility models and load models were examined. The aggregation of these models to new sub-transmission grid models shall help to identify the impact of renewable generation from a TSO's perspective. These models shall provide estimations on the safe side and allow the calculation of a mid-term frequency response of the system. Combined with test cases for system restoration studies, both aggregated and real grid models provided a sound basis for the following restoration strategy development.

New grid restoration strategies, in particular top-down, bottom-up or a combination of both were developed. Within these strategies, the influence of renewable energy sources was examined with the above-mentioned models. In addition, their potential active participation was taken into account. Subsequently, these strategies were optimized based on the quantification of economic costs and social welfare during the system restoration process while maintaining the system security.

To support grid operators during grid restoration, a demonstration tool was developed. The purpose of this tool is twofold: First, it shall improve the awareness by providing information about the actual system security level in terms of the current inertia, flexibility options and how much load and/or generation can be re-connected. Second, it shall provide decision support by proposing a set of fortunate next possible restoration steps. A step-by-step optimization is proposed reflecting today's operator practice instead of a global optimization approach, since the latter is likely to fail due to a lack of input data, possible unforeseen events and excessive computational effort. Based on the previous results recommendations and a roadmap for the migration towards the proposed system restoration plan are given, as well as requirements for renewable generators and recommendations for advanced control center features.

Power system models of Netz Oberösterreich GmbH and KNG Kärnten Netz GmbH were developed for a 2025 scenario with high shares of RES. The power system models include a residual load model for restoration studies. The residual load model consists of loads considering the cold load pick up effect, RES with their synchronization and start-up behaviour as well as battery energy storage systems (BESS). Besides, a central European transmission system model has been developed for a 2025 scenario.

In order to develop new grid restoration strategies, the grid restoration process was depicted as a very large tree-like directed acyclic graph. The roots of the graph differ depending on the start strategy and scenario. The end nodes represent either impermissible system states or full supply. As traversing the entire tree would be extremely time consuming, the probability to find valid paths through the graph was increased by using a method based on Monte Carlo tree search [10]. For this purpose, depth-first search (DFS) and breadth-first search (BFS) algorithms and an extensive parallelization were developed. By combining BFS and DFS algorithms, 400 random and different valid paths for the grids of Netz Oberösterreich GmbH and KNG Kärnten Netz GmbH were retrieved. To evaluate and compare the different grid restoration processes, Key Performance Indicators (KPIs) were developed. Global KPIs evaluate the whole restoration process, whereas Individual KPIs were defined for every restoration step. The analysis shows that a restoration with high shares of RES is feasible. Restoration processes with high KPIs were selected as favourable restoration strategies.

To support grid operators during grid restoration and to meet the new challenges posed by the massive installation of RES, a twofold operator tool has been developed. The awareness tool provides information about the actual system in terms of frequency stability and the associated maximum permissible load re-connection. In addition, non-meshed sub-stations are shown, which the operators should integrate into meshes. The active power flexibility diagram shows an overview of the residual load forecast and the current and future active power reserves. A security check calculates all actions by an operator prior to their execution with regard to their system response and thus avoids possible wrong decisions. The decision support tool provides concrete and advantageous switching operations for the actual grid restoration situation. Actions between network operators are negotiated and carried out via standardized interactions and communication interfaces. The tools were prototypically implemented in MATLAB / MATPOWER and associated graphical user interfaces were developed and connected to DUtrain's Power System Handler (PSH). The PSH is a real time dynamic training simulator with the purpose of training grid operators in a realistic control center replica. The operator tools were tested and verified in this simulation environment. The operator tools have been finally presented to the Working Group on Supply Security of Austria and an implementation roadmap [15] was established.

3.4. Achieved milestones

The following milestones during restoration have been achieved:

- State of the art grid restoration strategies have been analysed with regard to grid code requirements and grid operator handbooks.
- Restoration objectives and constraints were defined.
- Steady state models of renewable energy generation, storage facilities and loads have been developed and grid models/database are ready to study grid restoration strategies. Test case models for system restoration studies have been developed.
- Database for generation and load have been created.
- Future grid restoration strategies have been designed and optimized according to a defined target function.
- Grid restoration strategies were verified in the real time simulator.
- An awareness tool has been developed in order to support grid operators during grid restoration.

4 Project content and results

4.1. Network Restoration Strategy Matrix

RestoreGrid4RES considers the future renewable-based generation structure within the transformation to a renewable and ecological power supply. Besides coping with a high share of RES in normal grid operation, grid operation in emergency situations has to deal with this progression as well. As the risk of blackouts persists with growing integration of RES, it is important for network operators to investigate existing network restoration plans and adjust them to the new challenges. A restoration plan is a set of coordinated technical and organizational actions to bring the system back to the normal state after a blackout. It consists of re-energization, frequency management and resynchronization procedures [2].

The measures of the restoration plan are implemented in the transmission system by the transmission system operators (TSOs). TSOs in coordination with distribution system operators (DSOs), significant grid users (SGUs) and restoration service providers must activate the restoration plan process when the system is in an emergency or blackout state and keep the restoration plan updated. Each TSO has to inform the DSOs connected to the transmission system of measures to be implemented on DSOs installations, as well as on installations of SGUs, restoration service providers and DSOs that are connected to their distribution system. When a TSO notifies a DSO, the DSO shall immediately inform its SGUs, restoration service providers and connected DSOs in turn about the measures of the restoration plan, so that each involved DSO, SGU and restoration service provider can execute the restoration plan instructions released by the TSO.

4.1.1. Top-down and Bottom-up Re-Energization Strategies

In the (unlikely) event of a system-wide blackout, restoration strategies have to be available, which define how to restore the electricity system. As stated in Policy 5 “Emergency operations” of the ENTSO-E Continental Europe Operation Handbook, the related network restoration process for re-energization is mainly based on two principles, namely Top-down and Bottom-up re-energization strategies [4]. Their definitions are presented as following:

- Top-down re-energization strategy: “using external voltage sources from tie lines (the power from a secure system that can be the main ENTSO-E regional group continental Europe system) to re-energize a separated severely disturbed system”.
- Bottom-up re-energization strategy: “from self-reenergizing of parts of its own load-frequency control area to be ready for resynchronization with another area (that can be with the ENTSO-E regional group continental Europe main system)”.

According to Article 27 of the ENTSO-E Network Code on Emergency and Restoration, in case of blackouts, each TSO is entitled to combine Top-down or Bottom-up re-energization strategies as needed [2].

For the sake of clarity, a distinction of Top-down, Bottom-up and a combination of Top-down and Bottom-up is made as follows:

- Top-down strategy exclusively requires the assistance from neighbouring TSOs to re-energize the system of a TSO;
- Bottom-up strategy requires no assistance from other TSOs, but uses power sources with black start capability being available in the own control area of a TSO or subordinated DSOs for self-re-energization;
- Combinations of Top-down and Bottom-up re-energization strategies use the assistance of other TSOs as well as power sources with black start capability being available in the own control area of a TSO or subordinated DSOs for re-energization.

4.1.2. Build-down, Build-up and Build-together Re-Energization Strategies

The ENTSO-E network code only addresses the coordinated action and relationship between TSOs of different control areas during network restoration state. However, the responsibility of DSOs is not yet described in this code [5].

In the definition of the Bottom-up strategy, it is not defined whether black start is possible in the grid of the TSO, a distribution system operator (DSO) or both of them. Thus, a distinction of three new concepts of restoration strategies, i.e. Build-down, Build-together and Build-up, is introduced to clarify the actions that DSOs should take and the relationship between TSOs and DSOs. The three mentioned re-energization strategies are defined as following:

- “Build-down” means that no power source with black start capability is used in the distribution network. In this case, the assistance of the upstream TSO is required to re-energize the disturbed system of a DSO.
- “Build-together” indicates that there are power sources with black start capability in both the transmission and distribution network. The disturbed systems of a TSO and a DSO are self-re-energized separately.
- “Build-up” strategy means that no power source with black start capability is available in the transmission network, but only in the distribution network. The disturbed system of a DSO is self-re-energized and supports restoration of its upstream TSO.

4.1.3. Matrix of Network Restoration Strategies

The Build-down strategy can be applied together with either a Top-down or a Bottom-up re-energization strategy, or a combination of both. Build-together and Build-up cannot be applied with the Top-down strategy, but with the Bottom-up or a combination of Top-down and Bottom-up only. This is because Top-down defines that the restoration of a disturbed system is only based on the assistance from neighbouring secure TSOs, while both Build-together and Build-up indicate that network restoration is possible with the own black start power sources. Therefore, there are seven possible combinations of network restoration strategies as illustrated by the matrix in Figure 3. Build-down, Build-together and Build-up strategies can also be combined, as the restoration of the disturbed systems of several DSOs connected to the same TSO may be conducted in different ways. This is not shown in Figure 3 to avoid a further expansion of the matrix.

The sequence of restoration actions, including voltage forwarding, black start and resynchronization, is represented by circled numbers in the matrix in Figure 3. For example, following the combination of Bottom-up and Build-down re-energization strategies, black start in the disturbed network of TSO 2 is carried out at the beginning of the restoration state. After a complete re-energization, it is not defined whether TSO 2 forwards its voltage to the disturbed system of its subordinated DSO 2 or first synchronizes with the stable and secure neighbouring TSO 1 . This should be decided by involved TSOs and DSOs according to the actual situation.

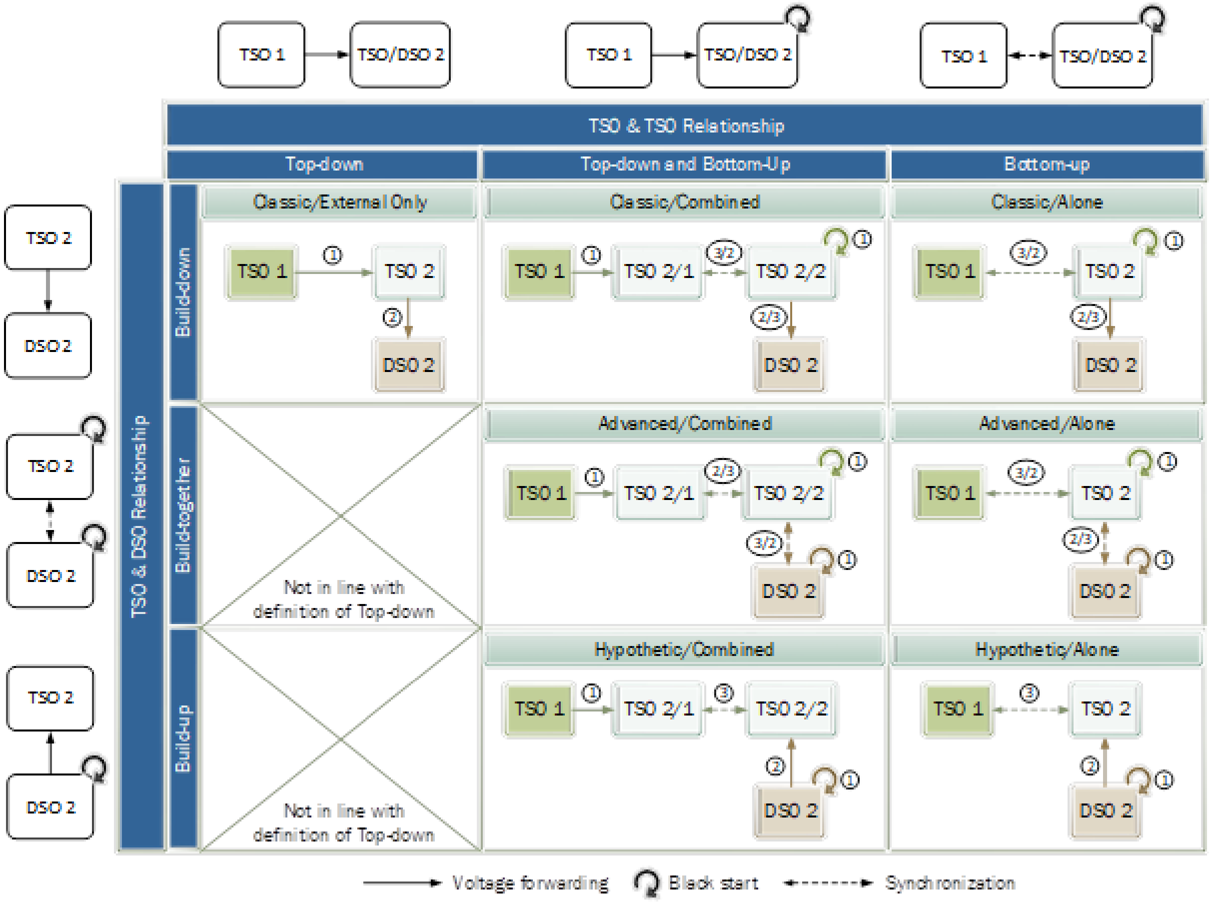

Figure 3. Matrix of network restoration strategies

A more intuitive way to name the network restoration strategies shown in Figure 3 is introduced as well. Each designation of those strategies consists of two parts, which represent the TSO-DSO relationship and the TSO-TSO relationship, respectively. The Build-down strategy is referred to as "Classic," as this strategy is so far designated to carry out network restoration from the transmission network to the distribution network. The build-together strategy is referred to as "Advanced", as high penetration of renewable energy sources increases generation capacity in distribution networks significantly and DSOs can use this to re-supply their customers independently from the TSO. Furthermore, it offers the potential to re-supply customers faster by a parallel network re-energization from the distribution and transmission network. The Build-up strategy is called "Hypothetic", because in this strategy, the TSO does not have its own power sources with black start capabilities or cannot deploy them. This does not consider the legal requirement that TSOs are responsible for system security in their control areas. Regarding the TSO-TSO relationship, the Top-down strategy is referred to as “External Only", as the network restoration is done exclusively with the assistance of other TSOs. Bottom-up is referred to as “Alone”, since network restoration does not require the assistance of a neighbouring TSO. As for the combination of Top-down and Bottom-up, it is called “Combined”.

4.2. Data analysis and modelling for distribution network

4.2.1. Development of dynamic load and generation models of renewable energy sources with limited data for grid restoration purposes

The model for the behaviour of loads during network reconstruction has been extended to include electric cars. The aggregated charging profile of electric cars differs from that in normal network operation, since the intended charging processes cannot take place during the blackout. Therefore, significantly higher charging power results at the time of re-supply than would be expected in normal operation.

The modelling of biomass and small hydropower plants was carried out analogously to the already developed models of photovoltaic and wind power plants. The model includes the synchronization conditions, the synchronization time, the power gradients during start-up and various control modes of the active power and reactive power management.

The developed models for renewable generators and storage as well as the load models were aggregated into a common residual load model. Subordinate networks with a high amount of renewable generation have an unfavourable behaviour, since the cold-load pick-up starts immediately after the re-supply. However, the renewable generators feed in with a time delay due to their synchronization time and the starting process, resulting in a "yo-yo effect".

4.2.2. Development of grid models

Models of artificial low and medium voltage grids have been developed to fully simulate the behaviour when connecting subordinate grids during grid restoration. Various rural, suburban and urban low-voltage networks have been developed, based on the building or geo-structural features such as typical network feeder length, distances between buildings and roads, number of outlets at the local network station and number of buildings or house connections. Based on usual network planning principles, the types of lines, network topologies and building methods of the lines for the different settlement structures were defined. Subsequently, the operating equipment, i.e. the transformers and the cables, were designed The modelling of the medium-voltage grids was carried out with a load density model, which reflects, for example, large load densities of densely populated urban areas with tall buildings or small load densities in the old town of small towns. The models were adapted to the Austrian conditions.

The developed PSR models represent residential loads with CLPU effect, PV converters with their synchronization and start-up behaviours, battery energy storage systems (BESS) and electrical vehicles (EV).

The CLPU is a phenomenon caused mainly by the loss of diversification among groups of thermostatic controlled loads (TCL) such as heat pumps, fridges, freezers, and boilers. The effect is shown by the active power peak value of a group of TCLs connecting to a network transformer at the instant of the re-energization, which can reach a value up to 2-3 times the one in normal operation by neglecting the fast transient process. The non-TCL (NTCL) devices such as TVs, washing machines, etc. can also contribute to the peak power according to their programming behaviour. Each category has its own models. The TCL models consist of the dynamic thermal models of residential buildings and TCL devices. The NTCL are further categorized into devices with auto-kick-in behaviours and those, which remain in stand-by modus at re-energization. These models are explained in detail in [6].

The PV-inverter model reflects the resynchronization and start-up behaviours based on [6], as well as the active power-frequency (P-f) response of the modern generation units based on [7]. The P-f response is active in the frequency interval between 50.20 Hz and the over-frequency protection setting (by default 51.50 Hz) with a dynamic slope, which is determined by the actual power generation. The BESS is assumed to have its own power converter independent of the PV-inverter, with no synchronization time requirement and no black start capability. It has a self-discharging behaviour during the power interruption and can cover the CLPU power peak fully or partially at the instant of re-energization depending on the power level and the state of charge (SOC) at that moment.

The charging time instants of the EVs are determined based on a probabilistic distribution function mentioned in [8]. If EVs are in charging mode at the exact time of the power interruption, they will continue their charging process at the time of re-energization. If the charging of EVs is planned to start within the power interruption interval, their charging plan will be shifted to the time of re-energization.

An aggregation of all abovementioned models for an outage duration of four hours on a working day in the summer of 2022 is illustrated in Figure 4. The aggregation consists of a network group with 100 households, each with an average installed PV capacity of 1.5 kW and a respective BESS. The aggregated BESS for the whole network group has 150 kWh storage capacity with a 75 kW loading power. There are 20 EVs in total.

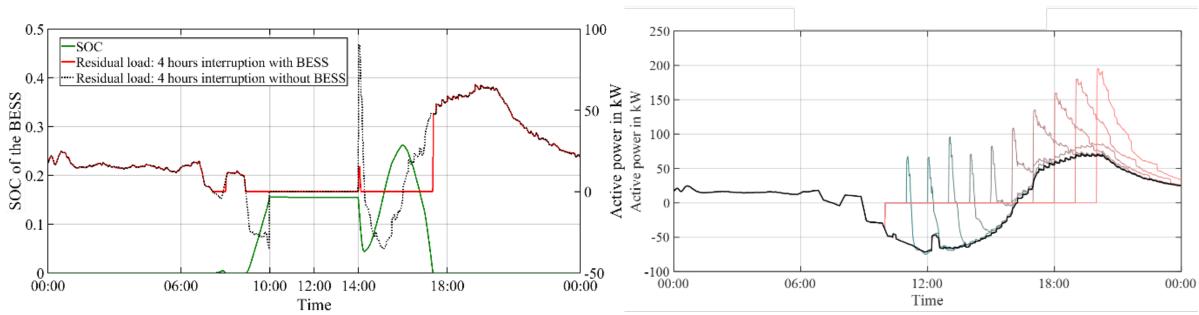

Figure 4: a) PSR model aggregation for a 4-hour power interruption with BESS details, b) PSR model aggregation for power interruption of variable duration without BESS details

The BESS starts with SOC zero as shown with the green solid line. The charging and discharging processes of the BESS are based on the residual load profile shown with the dotted black line. This curve represents the model aggregation without the BESS. The BESS is mainly loaded at around 9:00, as the residual load has a negative value. Due to the power interruption at 10:00 o'clock, the residual power becomes zero and the BESS starts to discharge due to its self-discharging effect. At the re-energization at 14:00, the battery kicks in immediately and covers a big part of the residual load. The BESS discharging power is limited and lower than the residual load power at the instant of the re-energization. Therefore, it cannot fully cover the residual load. The remaining residual load power has to be supplied from the external grid. It can be seen by the power peak at 14:00 o'clock in the residual load with a red solid line. When the PV generators kick-in a few minutes after the re-energization time, the residual load becomes negative again and the BESS is recharged. The BESS is fully discharged at around 17:00 and the red solid line returns to the residual load curve. The BESS is practically integrated into the PSR from the beginning of the re-energization for a duration of three hours. This results in an residual load of almost zero, seen from the external grid during this interval [3].

4.2.3. Development of a database

A power plant database for conventional power plants was created within the scope of the project for the purposes of the project. While it is not intended or designed for publication itself, the database contains the connection node, the power plant type (lignite-fired power plant, coal-fired power plant, gas turbine power plant, mineral oil power plant, gas and steam power plant, nuclear power plant, run-of-river power plant, pumped-storage power plant or storage hydropower plant), installed capacity and storage size (for pumped storage and storage hydroelectric power plants). The data was compiled from the power plant list of the Federal Network Agency, the Transparency Platform of the ENTSO-E and an internet research of the existing systems.

A database for renewable producers in Germany and Austria has been compiled from the annex register of the Bundesnetzagentur and data provided by the E-Control. The database contains the installed capacity and the geo-coordinates for each plant.

4.3. Optimization method

In the next step, new grid restoration strategies, in particular top-down, bottom-up or a combination of both approaches were developed and test grids were represented as graphs. Different types of searching algorithms were defined to find many possible paths to restore the grids for both KNG and NOOE networks. Global and individual key performance indicators were defined to verify that the network restoration paths are efficient and secure. In this context, a target function for the optimization process with a clear quantification of the solution quality and constrains was defined. Finally, the best strategies were selected and tested in real time environment.

4.3.1. Graph theory

Searching algorithms for graphs were needed to search for connected nodes or to traverse the entire graph. The Monte Carlo approach combined with depth first search (DFS), breadth first search (BFS), and random search are three mechanisms to identify edges and nodes in the graph and to find different paths to restore the power system. Furthermore, these search algorithms were computed in parallel on multiple processors to speed up the creation of possible restoration paths, namely parallel breadth-first search, parallel depth-first search and parallel own depth-first search (oDFS).

The edges are switching actions and nodes are grid states as shown in Figure 5. Each node in the network originates from its parent node, which in turn has a set of the children nodes. The root corresponds to the initial state, which may vary depending on the network restoration strategies. As depicted, dead end nodes define the states, where security limits are exceeded. If dead ends are found, alternative approaches starting at the same level for DFS or BFS will be tried. The end node is reached when more than 50% of the grid is successfully restored.

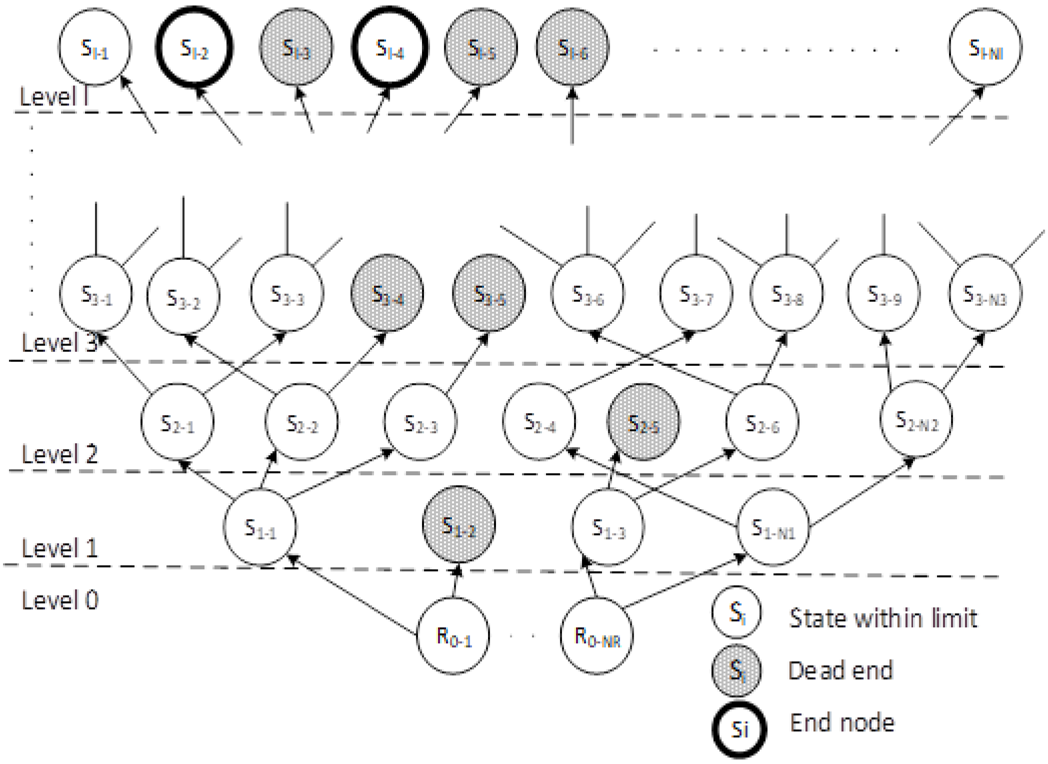

Figure 5: Graph theory for the creation of possible restoration paths

DFS stores the nodes in a stack (last-in, first-out). Starting with the newest node, the next node is searched to explore the graph. When new nodes are found, the algorithm searches the stack for nodes with undiscovered nodes to continue searching for new nodes. This method quickly leads away from the starting point. BFS stores the discovered nodes in a queue (first-in, first-out). This means the exploration of the graph starts from the oldest node in the queue and slowly radiates from the starting point(s) [9].

4.3.2. Parallel simulation by parallel processors

The total time for the load flow calculation and dynamic analysis for one path, including communication time between a 3.6 GHz processor and an external database, is 6-8 hours. To speed up the performance of path identification, either BFS or DFS, or a combination of both are carried out in parallel by running several MATLAB scripts among a number of processors on the most powerful Austrian supercomputer - Vienna scientific cluster (VSC-3).

Furthermore, to shorten the communication time and the time to store all calculated nodes, the indicated algorithms are extended to save the calculated children nodes on a MySQL database located at VSC.

As depicted in Figure 6, the search algorithm begins by expanding the initial state. All children nodes of initial states are calculated through parallel BFS by executing MATLAB scripts on parallel processors. Afterwards, all children nodes of nodes in level 1 are calculated up to a certain level (e.g. level 3 in this paper). The generated and stored children nodes from this level are defined as initial states for parallel oDFS. At each later step, one of the previously generated children nodes is expanded until an end node is reached. For generated paths, an end node is defined as having 50% of the total load supplied.

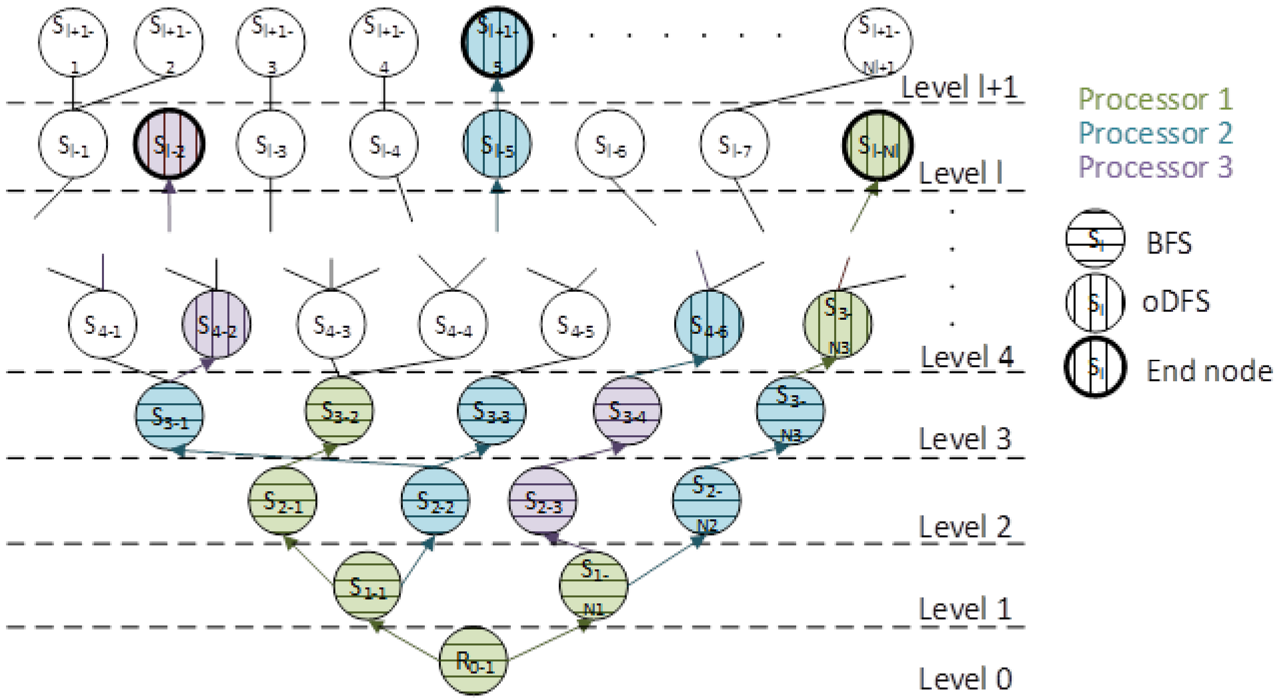

Figure 6: The combination of parallel BFS and parallel oDFS at VSC

For a random search, the next node for a processor to be explored is selected randomly out of all unexplored nodes, irrespective of its level. After choosing a random node, the calculation is performed as in the other algorithms mentioned above and all its possible children nodes are stored in the database. Thus, the graph can be built up completely randomly. This task is already completed [10].

4.3.3. Optimization approach

In order to restore networks fast, securely and efficiently after a blackout, all potential network restoration processes (global options) were modelled as a very large tree-like directed acyclic graph. The goal was to find a large number of different paths within the tree leading to full energy supply. The roots of the graph can be different depending on the restoration strategy chosen. As traversing the entire tree would be extremely time consuming, this can be achieved by running several MATLAB scripts in parallel. Furthermore, an external MySQL database is necessary to store all nodes. The flow chart of the algorithm is shown in Figure 7.The following flow chart represents static analysis of restoration and has already been completed. In the next step of the project, this algorithm will be extended through the dynamic analysis and the calculation of different types of strategies, which will be considered for the KPIs. This task is currently in working process.

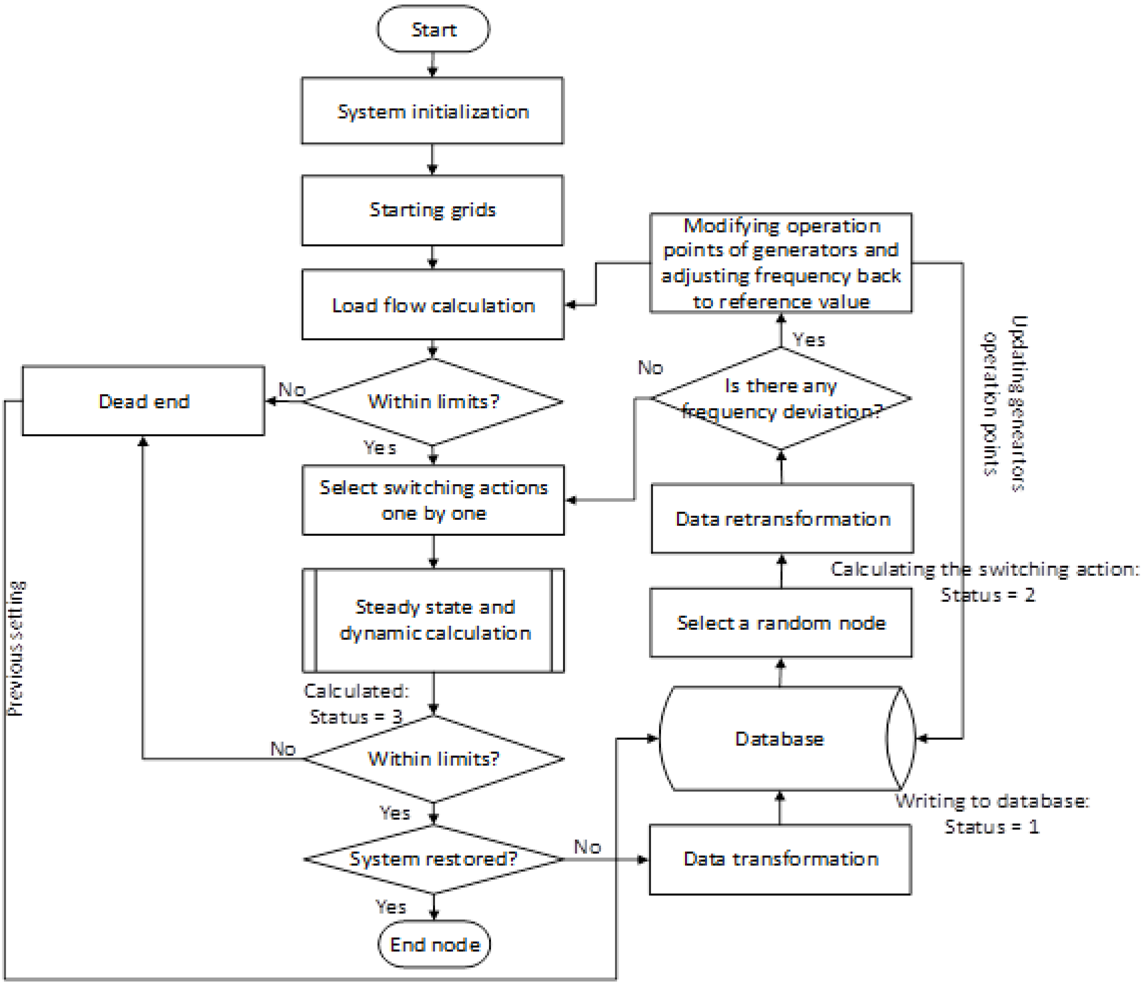

Figure 7: Overview of algorithm

The flow chart represents both the static load flow calculation and the dynamic analysis of restoration, which is executed in MATLAB.

In a first step, possible starting grids and their parameters are loaded into the simulation. Then, the strategic options including boundary conditions and influencing parameters, such as start-up frequency, voltage, maximum load and generation, have to be determined. If the system's physical values after an initial load flow calculation are within the critical limits, all individual possible actions for this system state will be performed, and the individual resulting network and its values ("node") are stored in a MySQL data base through a python file with a status of "1" (meaning "new node"). The next node in the database is selected among those existing nodes with "status 1" based on a strategy further described in [10]. The data of the selected node will be retransformed and prepared for the next calculation in MATLAB. Once the node is chosen, the status of this node in the database is changed to "2" (meaning "currently being explored") during the calculation to avoid that it is selected multiple times. After the load flow calculation and the creation of the multitude of resulting nodes, the status of the node is updated to "3" (meaning "explored") [9].

The steady-state frequency deviation that occurs during the restoration after loads or generators are connected is adjusted by modifying the operation points of the activated generators within their limits before a set of new switching actions is explored, mimicking automated or manual frequency restoration.

As can be seen, the network restoration process is simulated by carrying out different permissible switching actions and then performing a dynamic investigation and a load flow calculation. Available switching actions that are applied in the simulation include:

- Energizing power lines
- Energizing transformers
- Connecting loads
- Connecting generators

4.3.4. Dynamic analysis

For the performed simulation paths, the static characteristics of the system, the short-term (in the range of seconds) and the medium-term (in the range of minutes) dynamic characteristics of the system, such as frequency response, CLPU and the automatic or manual adaption of operation points of generators, are considered.

At first, all loads are determined. If the load is available and within the critical limits, the entire load is connected and supplied, otherwise it is switched on in 10 percent steps according to the frequency criterion. Furthermore, the cold load pickup will be developed according to the dynamic and static frequency deviation.

The generator units are assumed to ramp up to their operating point rather slowly after being re-synchronized, which leads to much less critical system dynamic behaviour than that caused by load re-connection. In order to avoid overloading of branches and voltage band violations after the load connection, the active power demand of the load is distributed over all active generators in the system participating in load-frequency control according to their droop settings. In order to recover the system frequency to its reference value, which can be selected deviating from 50 Hz, e.g. slightly higher, the active power set points of generators are adapted accordingly after the load connection. This task has already been completed.

The dynamic analysis was developed, which causes that after switching on the load, the frequency is checked and returned to the predefined frequency by the connected generators. According to this extension and considering on KPIs, different types of strategies will be developed to optimize searching paths. This task is currently in working process [9].

Based on the provided data by Austrian DSOs to investigate CLPU as well as the reconnection behaviour of DG, a distributed network model was developed and depicted in Figure 8. It has two voltage levels, namely 30 kV and 110 kV. The main components are a load with the power consumption of 21 MW, a 6.9 MW photovoltaic generator (PV), a 0.2 MW wind turbine generator, three transformers and a synchronous generator using the speed controller TGOV1 [11]. The aggregated load model accurately represents CLPU with the overload factor of 2.5 [12], and the behaviour of PV and wind generation follows the VDE-AR-N 4110 standard in the medium voltage level [13].

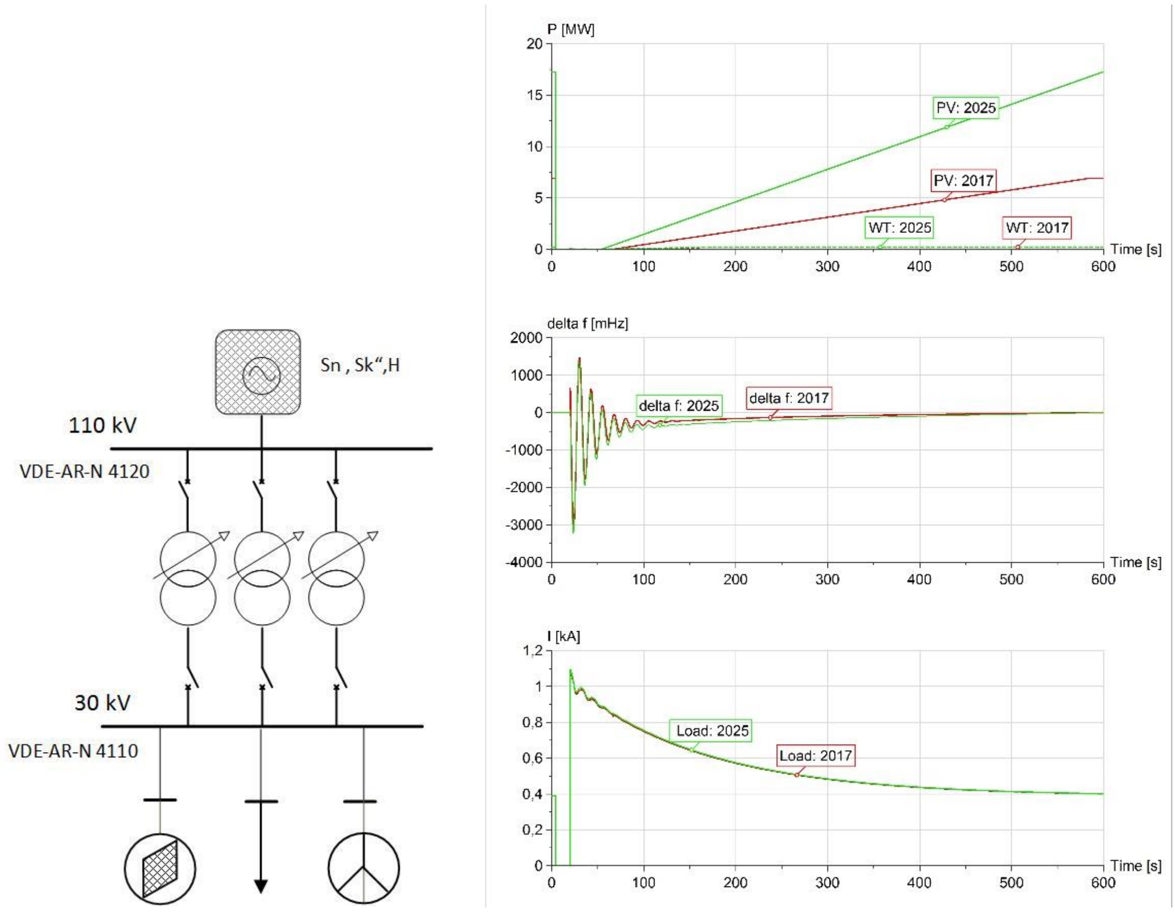

Figure 8: a) Distributed network model, b) Reconnection behaviour of PV, Frequency deviation, Cold load pickup for scenario 2017 and 2025

Based on the estimated values provided by Netz Oberösterreich GmbH the increase of the capacity of PV is scaled by +150% and that of wind generation by +10% in the year 2025. The PV reconnection behaviour, frequency deviation at 30 kV substation and CLPU are depicted in Figure 8 for both scenarios 2017 and 2025. The red line stands for scenario 2017 and the green line represents scenario 2025 [10].

4.4. Key performance indicators

For the system restoration process, global and individual key performance indicators (KPI) were defined. While global KPIs consider the total restoration process (or at least a significant period during the restoration process), individual KPIs are valid only for a specific state occurring during the system restoration.

Both kinds of KPIs are necessary to be applied to evaluate the possible restoration paths calculated by the optimization algorithm. Based on the calculated KPI, the relevant network restoration strategies are then allocated. The evaluation of global and individual KPIs were presented during the reporting period. This task has already been completed [9, 10].

4.4.1. Global KPI

Time to system restoration

T_{FSR} is the time elapsed from the beginning of the system restoration process until full system restoration

T_{ASR} is the time elapsed from the beginning of the system restoration process until restoration of critical auxiliary systems and/ or critical system parts (which need to be individually defined for the system, e.g. by a specific priority of the related loads and system parts)

Energy provided during system restoration

E_{FSR} is the energy provided during the entire system restoration process

E_{ASR} is the energy provided during the restoration process for critical system loads/ auxiliaries

With $P_{system}(t)$ being the total system load, and $P_{critical}(t)$ being the load of critical system parts/ auxiliaries, assuming system restoration process starts at t=0, this means

$$E_{FSR} = \int_0^{T_{FSR}} P_{system}(t)dt$$

$$E_{ASR} = \int_0^{T_{ASR}} P_{critical}(t)dt$$

This value needs to be normalized with the specific time required for system restoration, as otherwise restoration paths requiring more time are being overrated by this KPI.

$$P_{FSR} = \frac{\int_0^{T_{FSR}} P_{system}(t)dt}{T_{FSR}}$$

$$P_{ASR} = \frac{\int_0^{T_{ASR}} P_{critical}(t)dt}{T_{ASR}}$$

Thus, this KPI becomes the average power provided during system restoration.

Number of (switching) actions required

N_{SFSR} is the number of switching actions required until full system restoration

N_{FSR} is the number of actions required until full system restoration, with actions including specific operator activities apart from switching actions, e.g. change of set points

N_{SASR} is the number of switching actions required until critical system loads are served

N_{ASR} is the number of actions required until critical system loads are served, with actions including specific operator activities apart from switching actions, e.g. change of set points

Note: Most likely, N_{SFSR} will not differ that much for different system restoration paths, because at the end of the system restoration process, most switches will be closed, while at the start of the restoration process, most switches will be open.

Highest voltage deviation

With i being the number of nodes in the system, $v_i(t)$ being the voltage of each node over the system restoration time in p.u., the highest voltage deviation is

$$\Delta v_{max} = \max_{i,t} |v_i(t) - 1|$$

Integral of voltage deviation

As the single maximum value defined above may be caused by a singular situation during the system restoration process, it might be reasonable to consider an integral of this value over the restoration time. However, this would require normalizing the result with the total time to system restoration, as otherwise restoration paths requiring longer time might automatically be in disadvantage in this criterion, too.

$$\Delta v_{max,int} = \frac{\int_0^{T_{FSR}} \max_i |v_i(t) - 1| \, dt}{T_{FSR}}$$

Highest frequency deviation and integral of frequency deviation

Likewise, the highest frequency deviation and the integral of frequency deviation are defined as

$$\Delta f_{max} = \max_t |f(t) - f_0|$$

$$\Delta f_{max,int} = \frac{\int_0^{T_{FSR}} |f(t) - f_0| dt}{T_{FSR}}$$

Similarly, the distance of the actual frequency towards critical system frequencies (e.g. activating load shedding or disconnection of generation) could be defined as KPI.

4.4.2. Individual KPI

Inertia in the system

When $J_{system}(t)$ is defined as the total inertial mass of the system referred to nominal frequency $f_0 = \omega_0/2\pi$, the inertia constant of the system at a specific point in time can be defined as

$$H_{system}(t) = \frac{J_{system}(t) \cdot {\omega_0}^2}{2P_{system}(t)}$$

Size of the system

The size of the system can be described by

- the total length L(t) of energized lines, probably specified per voltage level,
- the total system load served $P_{system}(t)$,
- the total connected and available (and only partly used) generation capacity $P_{system,max}(t)$,
- the number of nodes $N_{nodes}(t)$ in the system,
- the number of loops (meshes) $N_{loop}(t)$ in the system.

The number of loops itself may be misleading. Probably it is better to define the percentage of nodes connected to radial branches in the system rather than the percentage of load connected to radial branches in the system, as these values better reflect the robustness against failures in the system.

Power reserve in the system

Active power reserve in the system can be defined as

$$P_{reserve,up}(t) = P_{system,\max}(t) - P_{system}(t)$$

$$P_{reserve,down}(t) = P_{system}(t) - P_{system,\min}(t)$$

Reactive power reserve can be defined in a similar way. It has to be considered that due to voltage restrictions the full capacity may not be usable. Moreover, positive and negative reactive power at different parts of the system might neutralize each other. However, as the system might most likely not be operated at maximum transmission capacity, reactive power will most likely be produced by the system and needs to be compensated by under-excited generation, so the devaluation value of the reactive power reserve could be useful.

$$Q_{reserve,up}(t) = Q_{system,\max}(t) - Q_{system}(t)$$

$$Q_{reserve,down}(t) = Q_{system}(t) - Q_{system,\min}(t)$$

System step load ability

$\Delta P_{max}(t)$ is defined as the maximum load step the system can support during transient conditions and in steady state without reaching critical frequency limits.

Number of possible paths to system restoration

Will be defined when we have more insight on the approach to find possible paths for system restoration

Number of good switching options

Will be defined when there is more insight into the approach to find possible paths for system restoration

Robustness against possible contingencies during system restoration

It might be possible to define this value based on other KPIs reflecting on the robustness (e.g. margin to limits, reserve left)

4.5. Awareness and supporting decision tool

To support grid operators during grid restoration and to meet the new challenges posed by the massive installation of RES, a twofold operator tool has been developed. The awareness tool provides information about the actual system in terms of frequency stability and the associated maximum permissible load re-connection. In addition, non-meshed sub-stations are shown, which the operators should integrate into meshes. The active power flexibility diagram shows an overview of the residual load forecast and the current and future active power reserves. A security check calculates all actions by an operator prior to their execution with regard to their system response and thus avoids possible wrong decisions. The decision support tool provides concrete and advantageous switching operations for the actual grid restoration situation. Actions between network operators are negotiated and carried out via standardized interactions and communication interfaces. The tools are prototypically implemented in MATLAB / MATPOWER and associated graphical user interfaces are developed and connected to DUtrain's Power System Handler (PSH). The PSH is a real time dynamic training simulator with the purpose of training grid operators in a realistic control center replica. The operator tools are tested and verified in this simulation environment. The operator tools have been finally presented to the Working Group on Supply Security of Austria and an implementation roadmap is established. This task is already completed.

An awareness tool is proposed that visualizes the following key information about the current state for each island-operated system part, beyond the capabilities of currently existing CC tools:

Grid frequency, substations with highest and lowest operational voltages, branch with highest loading, total frequency droop factor "s", dynamic frequency stability index, static frequency stability index, total mechanical start-up time T_A, maximum tolerable load pickup, maximum tolerable feed-in from RGU, re-supply rate (for the whole LFC area) and an active-power flexibility diagram.

The total droop factor "s" of each island is calculated using the individual droops of N active generators weighted according to their rated power. The smaller "s" is, the smaller is the static frequency deviation in case of an active power imbalance.

The dynamic frequency stability index describes the frequency sensitivity with respect to a sudden active power imbalance. For this purpose, the Awareness Tool evaluates the active power change ΔP and the maximum negative frequency deviation at each load pick-up. Figure 9 shows an example of the frequency response after a load re-connection of 10 MW in an islanded system with T_A = 10 s and synchronized generators with P_r = 3000 MW.

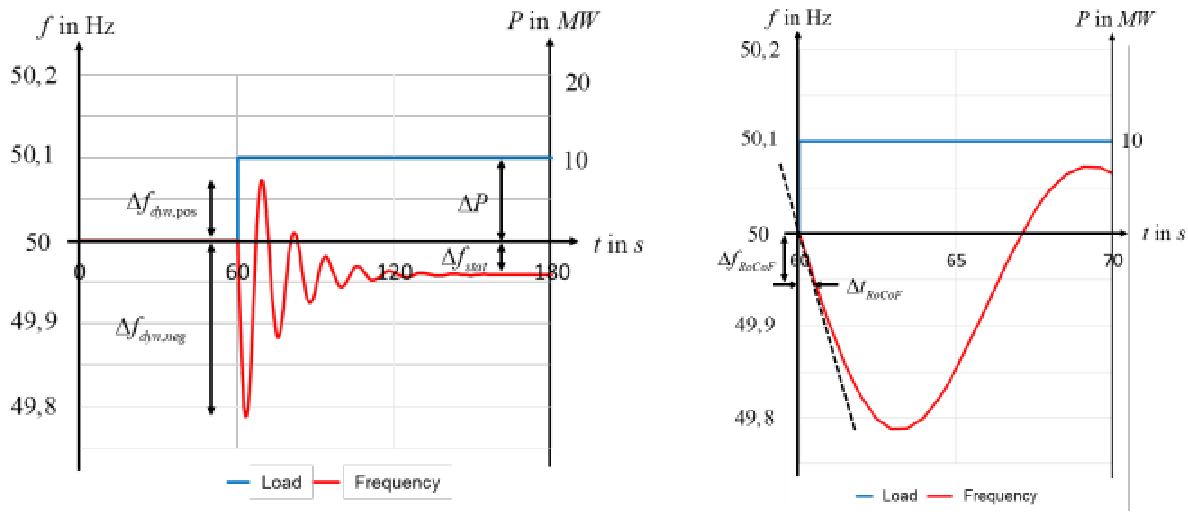

Figure 9: a) Frequency response, b) zoom in Figure a

In addition, the static frequency stability index describes the frequency deviation from the frequency set point in a quasi-stationary system state due to an active power mismatch. Since it is unlikely that a steady-state system condition will be reached, it is estimated based on the droops, the rated power of each power plant and the nominal frequency. The higher the static frequency stability index is, the more "stable" is the grid against active power imbalances.

Another proposed improvement is a Decision Support Tool that suggests the next restoration steps to operators. At each restoration step, the actual system status is analysed, all possible options are identified and their system responses are calculated. This full enumeration approach has a feasible computation time of less than 10 s for the prototype MATLAB implementation on a standard PC and thus meets the operator's requirement for a short response time. The Decision Support Tool classifies all restoration options into starting grids, seven categories for next restoration steps and impermissible options. [14]

5 Discussion

5.1. Network Topology

The simulation results of PSR are based on a real distribution grid with data provided by the Austrian DSO KNG-Kärnten Netz GmbH and Netz Oberösterreich GmbH, which are tested in this project by the offline method. The length of the high-voltage KNG-network is 850 km with 100% overhead power lines and the length of the 20 kV medium-voltage network is more than 5800 km, with 51% of overhead power lines. The network contains 215 branches (93 power lines and 122 transformers) within the interconnected 110 kV and 20 kV system and 158 busses. The model includes 37 generators.

The length of high-voltage in NOOE network is 1196 km, with 98% overhead power lines and the length of medium-voltage is 797 km with 65% overhead power lines. The network contains 182 branches, 65 generators and 216 buses.

5.2. Results and discussion

Figure 10 gives an overview of all simulated paths investigated in this report. The total load of the system in full operation in the study case is 750 MW, which means that the system is assumed to be successfully restored if more than 375 MW load in the network is supplied. The load supply P_{supply} of every path over its entire restoration time T_{supply} is shown in Figure 10. As can be seen, the 30 randomly generated paths are different from each other.

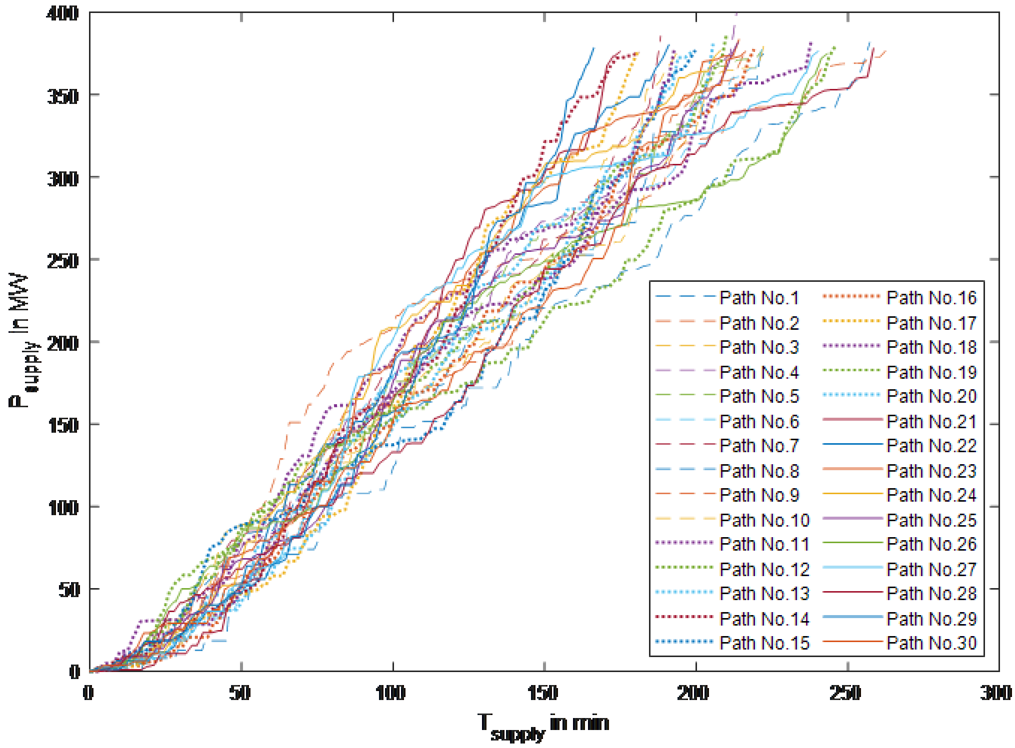

Figure 10: Overview of P_{supply} for 30 paths

The values of indicated KPIs for the exemplary 30 paths are given in Table 2 in chapter 8 (attachment). The values of the power supply of the load demand, the active power reserves and the power infeed of the RES are acquired at $t = T_{supply}$, when the last switching action step N is carried out to reach 50% of the total load supply. Depending on the load size that is chosen for the last step of the switching action for the successful restoration, the load supply $P_{supply}(N)$ at the end of one path can be larger than 375 MW. For example, in path No.4 the maximum load step that can be supported during the last switching action is approximately 41 MW. As long as the load step size is smaller than 41 MW, it can be switched on without reaching system critical limits. Therefore, $P_{supply}(N)$ reaches 399.92 MW by carrying out 26 MW load step from the second last status with $P_{supply}(N-1)$ being 373.92 MW.

Concerning the time to system restoration (T_{supply}) as shown in Figure 11, the path No. 29 has the shortest restoration time being 166.16 min to reach a 378.60 MW load supply with 229 switching actions and the path No. 9 requires the longest time of 262.50 min for a 376.80 MW load supply. The maximum load step connection of path No. 29 is 38.98 MW and the upper active power reserve is 621.84 MW.

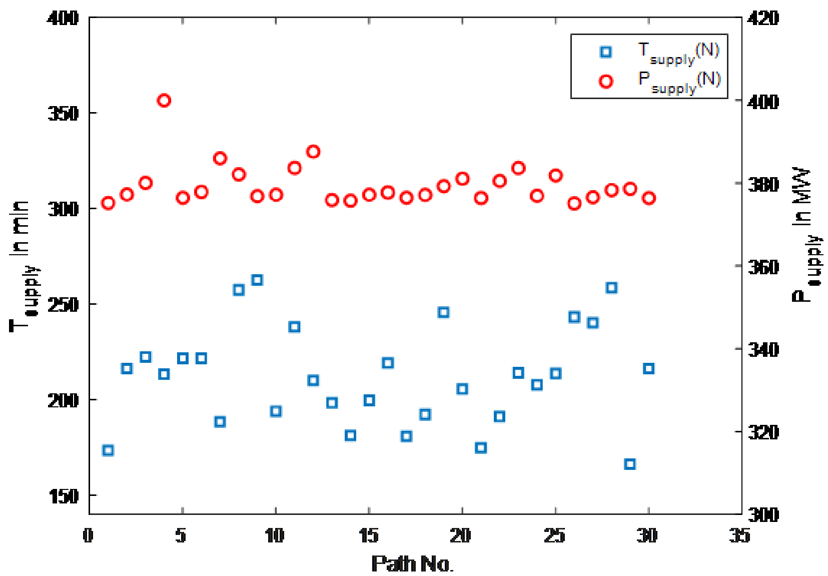

Figure 11: Overview of T_{supply} and P_{supply} for 30 paths

In Figure 12, the comparison between the shortest and longest path for 50% of load power demand is shown. As can be seen, path No. 29 has a lower power supply than path No. 9 until 127 min after the start of system restoration. Afterwards, the rate of change of power supply of path No. 29 becomes much larger than that of path No. 9, therefore path No. 29 needs less switching actions and reaches 50% of load supply earlier than path No. 9. The amount of connected RES is higher than for path No. 29. The reached average value of maximum load step is nearly 26.12 MW for path No. 29. As described in the earlier work [2], active power of generators is distributed over the load demand in the network. Since the load is reconnected stepwise during the PSR process, generators' active power is adjusted correspondingly as shown in Figure 12.

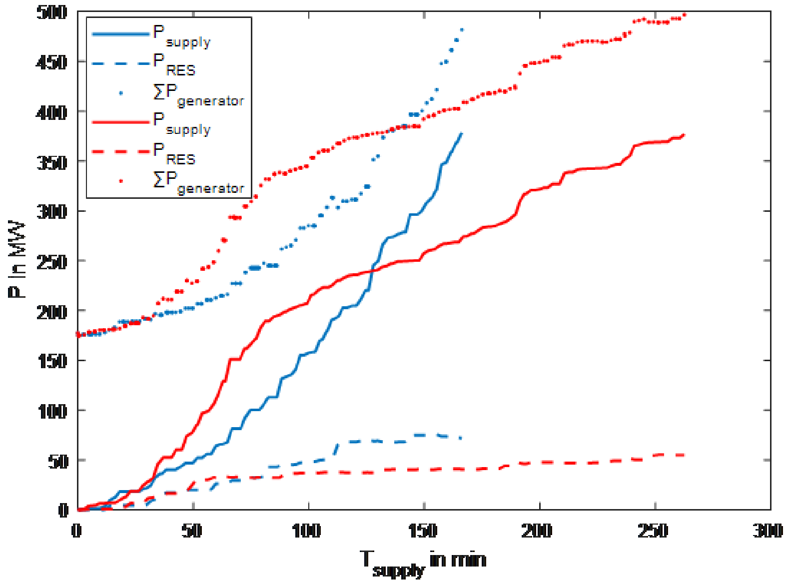

Figure 12: Comparison between path No. 29 (blue) and path No. 9 (red)

Regarding the average maximum load steps, the path No. 10 has the highest value of $\overline{\Delta P_{max-load}}$ $\Delta P_{max-load}$ whereas the path No. 15 has the lowest value. Path No. 30 has the highest value regarding the maximum load steps reaching in the last steps of restoration. Figure 13 shows an overview of $\Delta P_{max-load}$ and $\overline{\Delta P_{max-load}}$ for 30 paths.

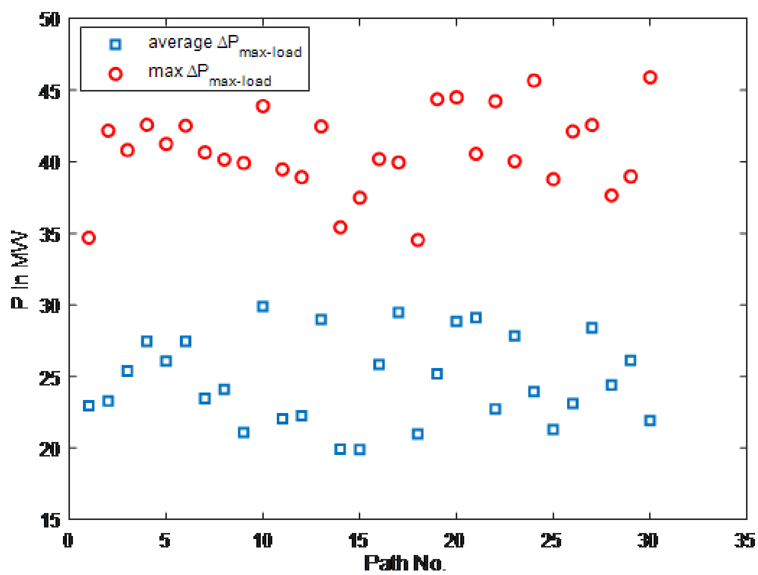

Figure 13: Overview of $\Delta P_{max-load}$ and $\overline{\Delta P_{max-load}}$ for 30 paths

Figure 14 shows a comparison between path No. 10 and path No. 15 concerning the system power demand. Their DG's active power is relatively similar. The difference of the required time for a system restoration of 50% between these two paths is 5.6 min. As shown in Table 2, there is a difference of 8 MW of active power reserve in the last step of both paths.

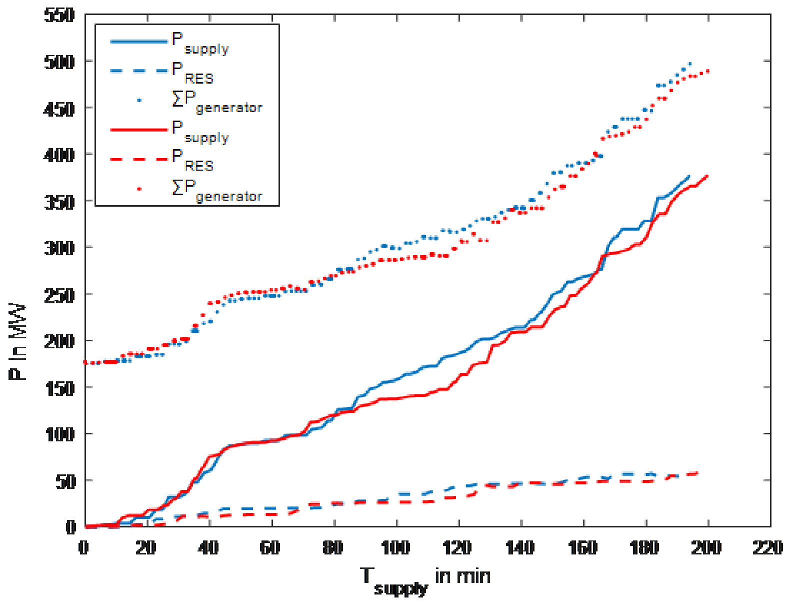

Figure 14: Comparison between path No. 10 (blue) and path No. 15 (red)

Regarding the power reserve, the path No. 1 has the lowest value of RES infeed of 39.6 MW by the end of restoration, which leads to a lower value of upper power reserve. In opposite, path No. 6 has almost 98.66 MW RES infeed by the end and it has a higher power reserve. Figure 15 shows the comparison of power reserve of all indicated paths.

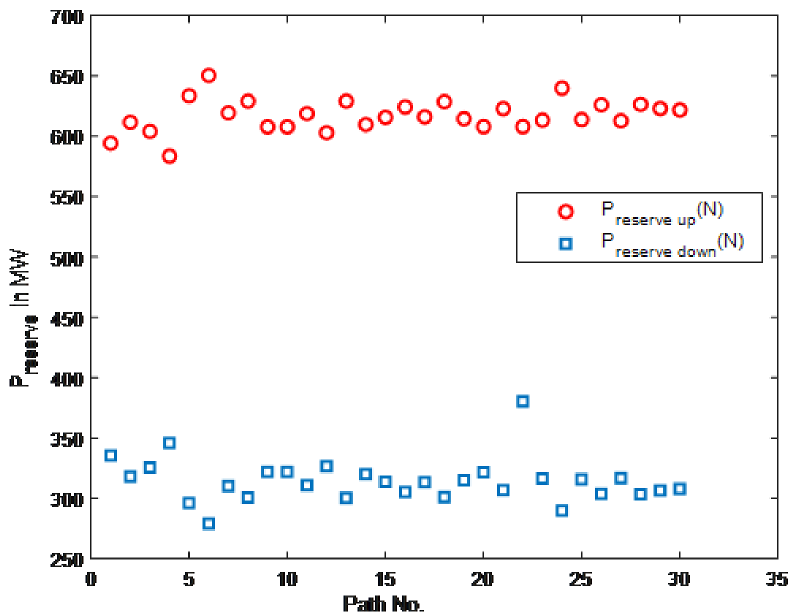

Figure 15: Overview of power reserve for 30 paths

Figure 16 shows the RES infeed and load power demand during the restoration process for both paths. Path No. 6 takes longer to supply 377.85 MW at 221 min and shows a higher average load step ability during the restoration.

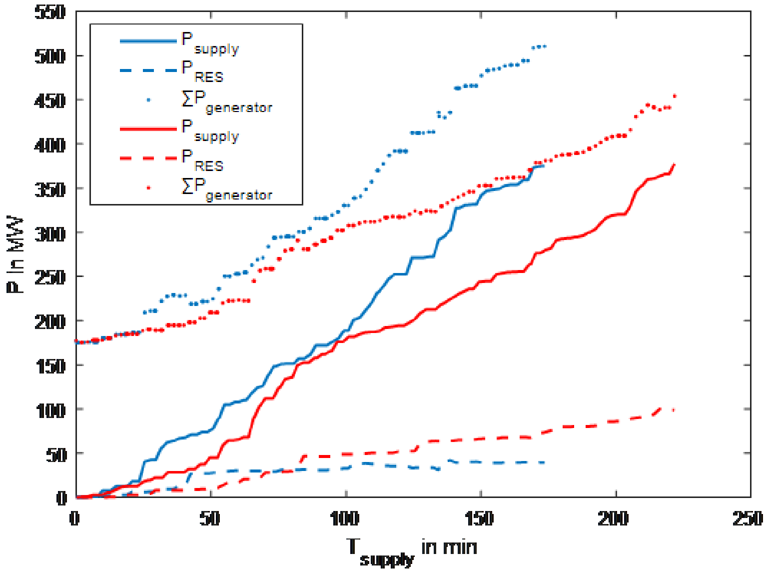

Figure 16: Comparison between path No. 1 (blue) and path No. 6 (red)

6 Conclusions and Outlook

RestoreGrid4RES faces the future renewable based generation structure within the transformation to a renewable and ecological power supply. Besides coping with a high share of renewable energies in normal grid operation, grid operation in emergency situations has to deal with this progression as well. In the unlikely event of a system-wide blackout, restoration strategies are needed, which define how to restore the electricity system. This determines the aim of the project, which is to ensure a fast but secure grid restoration after a system-wide blackout in networks with high renewable energy generation.

Therefore, two main targets had to be achieved. First, by taking into account the modified cold load pick-up behaviour of networks including distributed generation, new grid restoration strategies were developed to answer the question of how grid restoration can be accomplished without interference by distributed renewable energy technologies. Moreover, it was examined how renewable energy technologies may be actively used in the restoration process and what ancillary services or requirements they have to fulfil. Second, because of the need for new, trustworthy, robust and secure operator tools, an innovative restoration tool was developed to guide the operators during grid restoration and to provide information about possible next steps and their consequences. Specifically, following topics have been worked on:

- As a first step, a review of current practices for a system restoration process was conducted – with consideration of the legal framework and technical requirements. Thereby, also limitations of current practices were identified - based on the vast experience of Austrian distributed system operators involved in the project.
- Steady state models of renewable energy technologies were developed to analyse the impact of renewable generation on grid restoration.
- New grid restoration strategies, in particular top-down, bottom-up or a combination of both approaches were developed under consideration of lessons learned from Austrian stakeholders and project partners. In this context, by use of the previously developed models, the influence of renewable energy technologies as well as their possible proactive use was examined. Derived strategies were optimized based on quantification of economic costs and social welfare impacts [15].
- Finally, based on previous outcomes, recommendations and a roadmap for migration towards the proposed system restoration plan were derived, which can be used by other Austrian system operators as well.

The new developed restoration strategies with specific consideration of possibly active use of renewable and distributed generation resulted in new recommendations on grid codes for emergency and restoration with respect to the ancillary services that these generators have to provide to successfully contribute to the overall system restoration process. While many smart grid projects focus on small smart grids (micro-grids), this project took the whole Central European transmission system into account, of which the Austrian system is an integrative part, and thus gained a high scaling potential. The project provided a transparent overview of current grid restoration approaches. Thereby, it enabled an assessment of the suitability of these approaches in the changing environment by increased installation of distributed energy resources. Thus, it allowed a gap analysis and identification of necessary steps for Austrian system operators to adapt these approaches under new system conditions.

7 Verzeichnisse

Abbildungsverzeichnis

Tabellenverzeichnis

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Abkürzungsverzeichnis

BESS	Battery Energy Storage System
BFS	Breath First Search
BSU	Black Start Unit
CC	Control Center
CLPU	Cold load pickup
DFS	Depth First Search
DSO	Distribution System Operator
EnWG	Energie Wirtschaftsgesetz
ENTSO-E	European Network of Transmission System Operators for Electricity
EV	Electric vehicle
KNG	Kärnten Netz GmbH
KPI	Key Performance Indicator
LFC	Load frequency control
NOÖ	Netz Oberösterreich
NTCL	non-thermostatically controlled load
oDFS	Own Depth First Search
PC	Personal computer
PSH	Power System Handler
PSR	Power System Recovery
PV	Photovoltaic
RES	Renewable Energy Sources
RGU	Renewable generation unit
SAIDI	System Average Interruption Duration Index
SOC	State of charge
TCL	thermostatically controlled load
TSO	Transmission System Operator
TUKL	Technische Universität Kaiserslautern
TUW	Technische Universität Wien
TV	Television
VSC	Vienna Scientific Cluster
WP	Work Package

8 Anhang

Table 2: Values of KPI for 30 paths

No.	N	T_{supply} /min	$P_{supply}(N)$ /MW	$\overline{\Delta P_{max-load}}$ /MW	$max(\Delta P_{max-load})$ /MW	$P_{\mathrm{reserve,up}}(N)$ /MW	$P_{\mathrm{reserve,down}}(N)$ /MW	$P_{\mathrm{RES}}(N)$ /MW
1	224	173.50	375.19	22.96	34.69	594.23	335.42	39.76
2	270	216.33	377.22	23.29	42.18	611.65	318.00	59.21
3	264	222.33	380.00	25.37	40.81	604.07	325.58	54.41
4	251	213.16	399.92	27.46	42.58	583.58	346.07	53.84
5	279	221.50	376.41	26.07	41.25	633.50	296.15	80.25
6	264	221.66	377.85	27.45	42.52	650.47	279.18	98.66
7	231	188.33	385.97	23.46	40.65	619.42	310.23	75.74
8	288	257.33	382.09	24.10	40.16	629.12	300.53	81.55
9	302	262.50	376.80	21.07	39.91	607.81	321.84	54.95
10	249	194.00	377.16	29.88	43.90	607.79	321.86	55.30
11	287	238.00	383.63	22.05	39.47	618.78	310.87	72.96
12	245	210.00	387.56	22.24	38.92	602.99	326.66	60.89
13	239	198.33	375.89	28.98	42.47	629.17	300.48	75.41
14	226	181.16	375.75	19.93	35.43	609.68	319.97	55.77
15	254	199.66	377.15	19.90	37.49	615.70	313.95	63.19
16	270	219.16	377.70	25.84	40.20	624.26	305.39	72.31
17	235	180.83	376.43	29.47	39.96	616.10	313.55	62.87
18	237	192.26	377.12	20.98	34.54	628.67	300.98	76.13
19	284	245.66	379.24	25.17	44.37	614.55	315.10	64.13
20	263	205.50	381.04	28.84	44.50	607.94	321.71	59.33
21	227	174.83	376.36	29.11	40.55	622.91	306.74	69.62
22	239	191.00	380.48	22.73	44.24	607.93	380.48	58.75
23	259	214.00	383.60	27.84	40.04	613.36	316.29	67.31
24	255	207.83	376.89	23.95	45.67	639.82	289.83	87.06
25	259	213.66	381.83	21.29	38.78	613.86	315.79	66.04
26	288	243.16	375.09	23.11	42.13	626.05	303.60	71.49
27	292	240.16	376.54	28.39	42.57	612.85	316.80	59.74
28	305	258.50	378.29	24.40	37.65	626.41	303.24	75.05
29	229	166.16	378.60	26.12	38.98	622.96	306.69	71.90
30	259	216.33	376.35	21.91	45.91	621.84	307.81	68.53

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