# PARALLEL BREADTH- AND DEPTH-FIRST MONTE CARLO TREE SEARCH ALGORITHMS FOR INVESTIGATING POWER SYSTEM RESTORATION

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**Abstract:** The project RestoreGrid4RES investigates a fast, secure and reliable restoration after blackouts, which is of great importance. For the purpose of the project, an automated power system restoration algorithm is developed for investigating different power system restoration strategies which could be implemented in real systems. This algorithm is programmed in MATLAB and includes load flow calculation and evaluation of the system's dynamic behavior during the restoration. Moreover, depth-first and breadth-first search based on Monte Carlo approaches are implemented to identify possible power system restoration paths. Both search algorithms can be carried out in parallel to speed up the calculation.

In this paper, the parallel breadth-first search and parallel own depth-first search are addressed and the related simulation results are presented. For the evaluation of all generated possible paths, key performance indicators are implemented for the assessment of grid restoration options.

**Keywords:** Power system restoration, parallel breath-first search, parallel own depth-first search, individual key performance indicators

## 1 Introduction

Blackouts are rare events, and have major consequences on economy and society as recently reported worldwide [1]. Therefore, the project RestoreGrid4RES aims to support a fast and secure grid restoration in case of a blackout in networks with a high share of renewable energy generation. In early stages of restoration, cold load pick up and automatic synchronization of renewable energy sources (RES) can cause system instability. Moreover, a bulk resynchronization of large quantities of distributed generation at a later stage might cause problems, too. Considering the mentioned challenges as well as power system static and dynamic characteristics, an automated power system restoration (PSR) algorithm, including both load flow calculation and the evaluation of the system's dynamics, is developed in the previous work [2] to keep the voltage and frequency within allowable limits during the whole PSR process.

In the proposed path identification algorithms, the breadth-first search (BFS) and depth-first search (DFS) based on Monte Carlo approach are applied to take a random next available switching action during PSR, so that a full or partial restoration path is built up at the end of one cycle of a calculation process. Furthermore, these search algorithms are computed in parallel on multiple processors to speed up creating possible PSR paths, namely parallel breadth-first search, parallel depth-first search and parallel own depth-first search (oDFS). In this paper, only parallel BFS and parallel oDFS are presented.

For the evaluation of all generated possible PSR paths, key performance indicators (KPI) are implemented. Based on the evaluation of KPI, possible paths can be put into different categories of power system restoration strategies based on the developed matrix of network restoration strategies in [3].

This paper is organized as follows: Section 2 describes the principle of parallel BFS and parallel oDFS. Section 3 presents individual KPI. A description of the network model and simulation environment as well as the evaluation of simulation results are given in section 4.

# 2 Methodology

PSR is represented as a high dimensional tree that is explored by BFS and DFS based on the Monte Carlo approach [4]. The search algorithms make a random decision among those available samples that are calculated and evaluated to be within system security limits. This leads to an asymmetrical tree over time [5].

According to the graph theory, the high dimensional tree consists of a root, a set of edges and a set of nodes [6]. The root corresponds to the initial state, which may vary depending on the network restoration strategies. Following a Build-up strategy as described in [3], starting grids contain black start units. An edge represents a switching action per PSR step, which includes energizing power lines or transformers, connecting load or synchronizing generators. A node illustrates a grid state after a switching action being conducted.

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)[1].

The number of generated nodes is enormous and may increase exponentially until certain levels. Therefore, the number of calculated paths can be significant, depending on the amount of grid elements and system dynamic characteristics. For example, in the Kärnten Netz GmbH (KNG) - 110 kV network with 158 buses, approximately 300 switching actions are required to re-supply 50% of total load. Furthermore, to shorten 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.

[1] http://vsc.ac.at/

BFS always starts with the currently lowest level of stored unexplored nodes, which makes the root of the tree wider. DFS takes and calculates one of the last generated unexplored nodes, which means a fast growing tree. BFS and DFS can be implemented in parallel, namely different processors execute several MATLAB scripts with the same algorithm (BFS or DFS) at the same time. In addition, parallel oDFS means that MATLAB scripts are run on different processors and each processor can only access its own created unexplored nodes. This paper focuses on the sequential combination of parallel oDFS and parallel BFS considering static load flow, dynamic frequency deviations and cold load pickup.

As depicted in Figure *1*, 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.

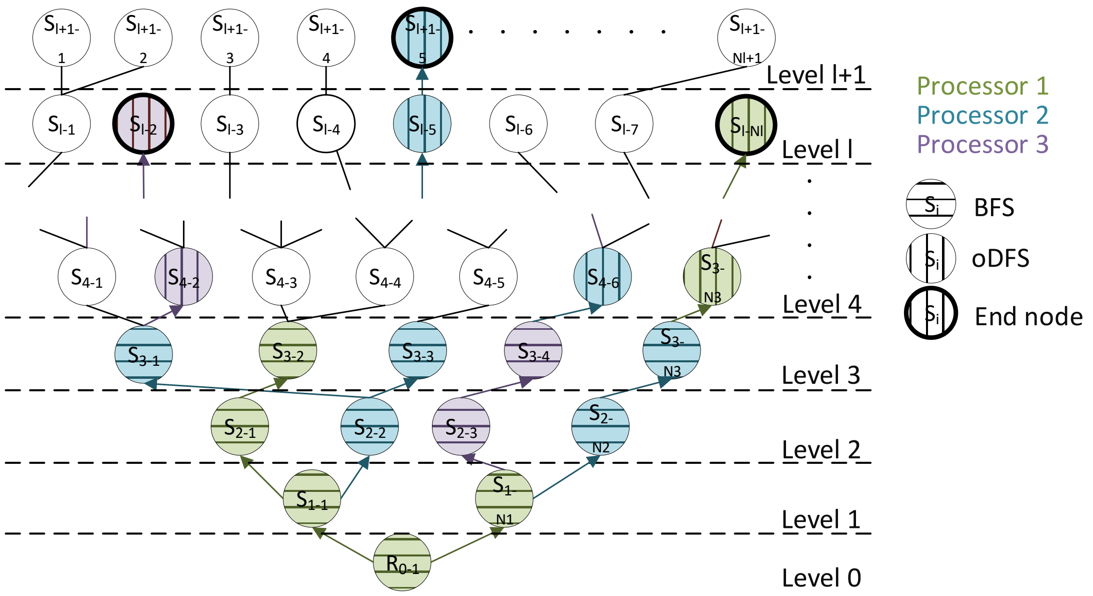


Figure 1: The combination of parallel BFS and parallel oDFS based on Monte-Carlo approaches

## 3 Key Performance Indicators

Global and individual KPI are defined to evaluate possible PSR paths. Some representative global KPI, such as speed of restoration, the required number of switching actions, energy provided during restoration, maximum and minimum voltages as well as static and dynamic frequency deviation, are presented in [2].

Apart from those global KPI, individual KPI are introduced and investigated in this paper. Individual KPI are valid only for a specific state occurring during the system restoration. Generally, any individual KPI may be made global by integrating or averaging it over the system restoration time. However, a normalization may be necessary if PSR paths with different PSR times are compared, as these values might differ significantly.

System step load ability is defined by the maximum load step $\Delta P_{max\text{-}load}(t)$ that the system can support during transient conditions and in steady state without reaching critical frequency limits. The average of maximum load step is defined as the sum of the maximum load steps of each level *n* divided by *N*, which is the number of all required switching actions for restoration and *n* is the index of switching action.

$$\overline{\Delta P_{\text{max}-load}} = \frac{\sum_{n=1}^{N} \max|\Delta P_{max-load}(t)_n|}{N} \qquad (1)$$

Besides, active power reserves in the system, $P_{\text{reserve,up}}(t)$ and $P_{\text{reserve,down}}(t)$, are defined as:

$$P_{\text{reserve,up}}(t) = P_{\text{system,max}}(t) - P_{\text{supply}}(t) \qquad (2)$$

$$P_{\text{reserve,down}}(t) = P_{\text{supply}}(t) - P_{\text{system,min}}(t) \qquad (3)$$

where $P_{supply}(t)$ is the lumped load active power that is currently supplied by the system, i.e. the share of load of the system not supplied by distributed (renewable) generation $P_{RES}(t)$. $P_{\text{supply,max}}(t)$ and $P_{supply,min}(t)$ are the maximum and minimum operation points of the connected available centralized generation capacity, respectively. The same approach is possible for reactive power. However, reactive power reserves are not further addressed and analyzed in this paper. A combination of global and individual KPI gives a suggestion which PSR path is best, meaning the most efficient, reliable and secure path.

# 4 Results Represented by Key Performance Indicators

## 4.1 Case study

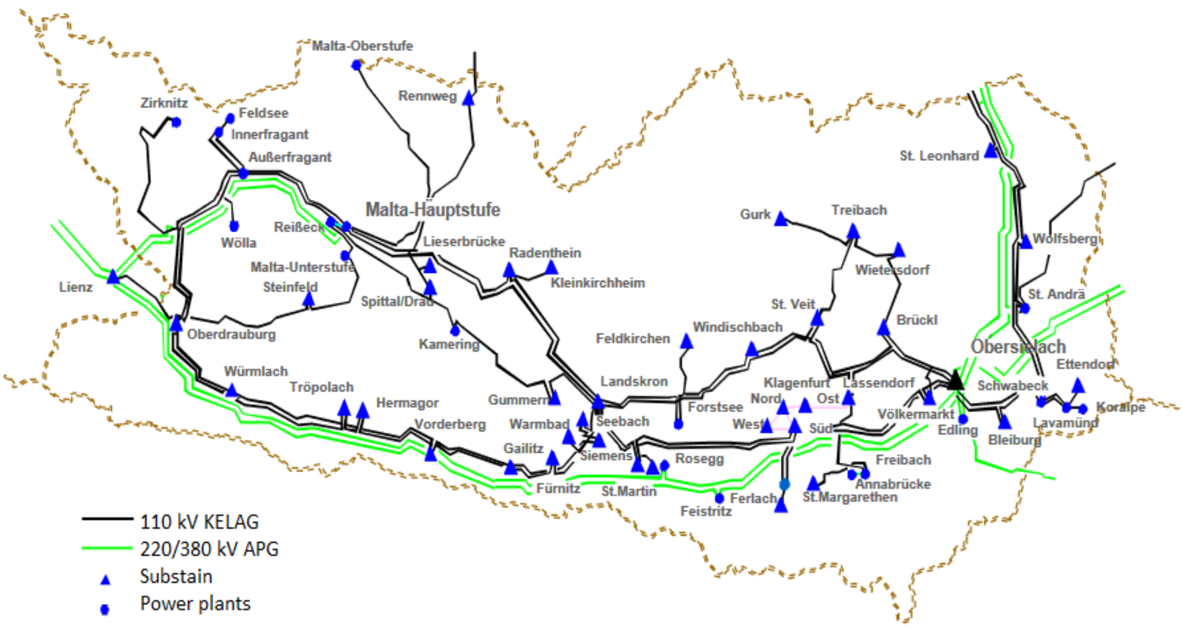


Figure 2: The 110kV grid of Kärnten Netz GmbH (KNG)

The proposed algorithms are performed on multiple processors on the Vienna Scientific Cluster and implemented in MATLAB R2016b. In order to perform load flow calculations, MATPOWER package 5.1 is applied. Python code is utilized to achieve communication between processors and the database. As depicted in Figure *2*, a 158-bus representation of the 110 kV KNG grid is used as a study case to calculate exemplary 30 PSR paths with the proposed algorithms.

Based on the developed PSR strategy matrix, a combination of the Bottom-up and Build-up strategy is applied. The initial state is the KNG starting grid with its own black start units being activated. In order to compare the different simulated paths and to analyze the KPIs, 50% supply of total load demand is defined as the system being successfully restored.

The required time for load reconnection is assumed to be 120 s because of system dynamic frequency response after cold load pick up. The idle generators are re-energized and slowly ramped up to their operating point to get ready for re-synchronization. The time for generator re-synchronization is thus set to 90 s. Furthermore, the active power of load demand is distributed over all activated generators. The time that is assumed for re-energizing power lines or transformers by network operators is 10 s.

## 4.2 Analysis of KPI

*Figure 3* gives an overview of all simulated paths investigated in this paper. The total load of the system in full operation in the study case is 750 MW, which means that 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. As can be seen, the 30 randomly generated paths are different from each other.

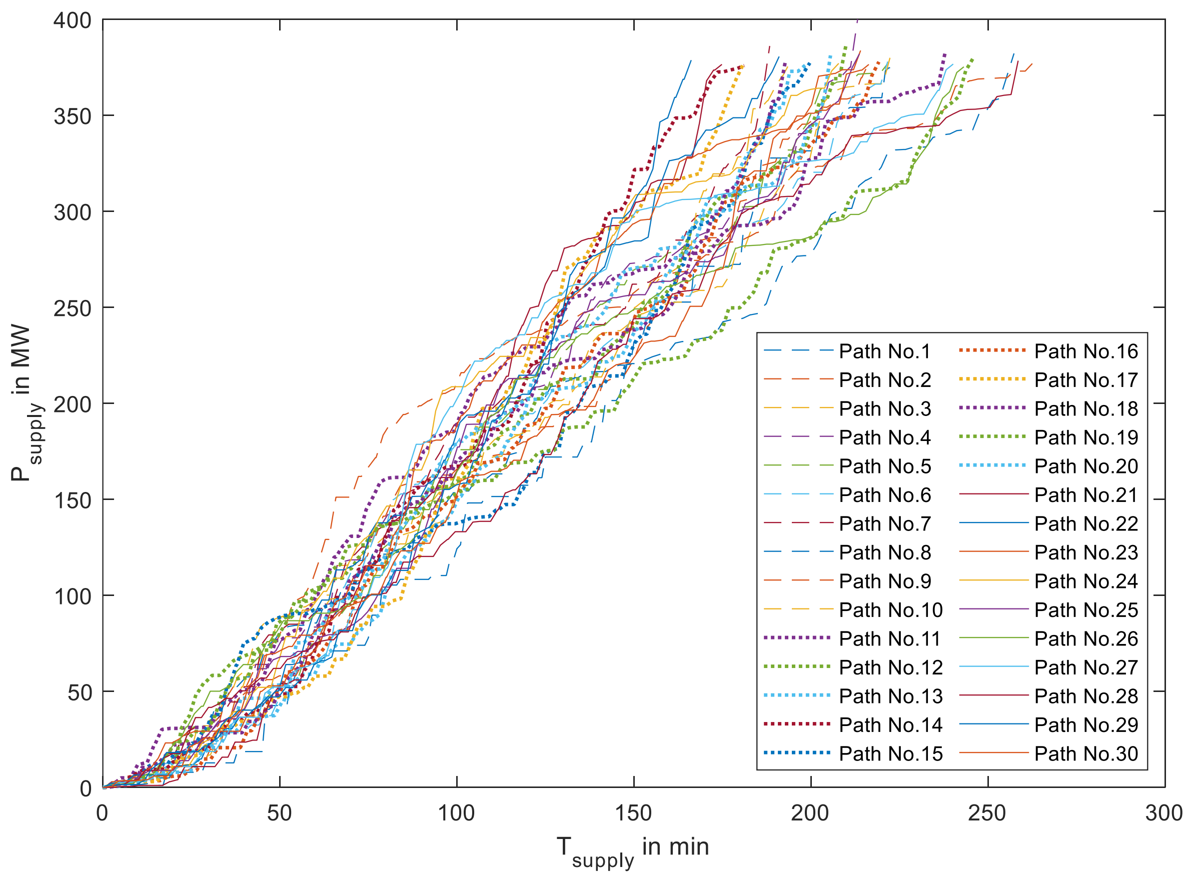


Figure 3: An overview of $P_{supply}$ for 30 paths

Table 1: The 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 |

The values of indicated KPIs for the exemplary 30 paths are given in Table *1*. The values of power supply of load demand, active power reserves and power infeed of RES are acquired at $t$ = $T_{supply}$, when the last switching action step *N* is carried out to reach 50% of total load supply. Depending on the load size that is chosen for the last step of switching action to 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 is *Figure 4*, 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 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.

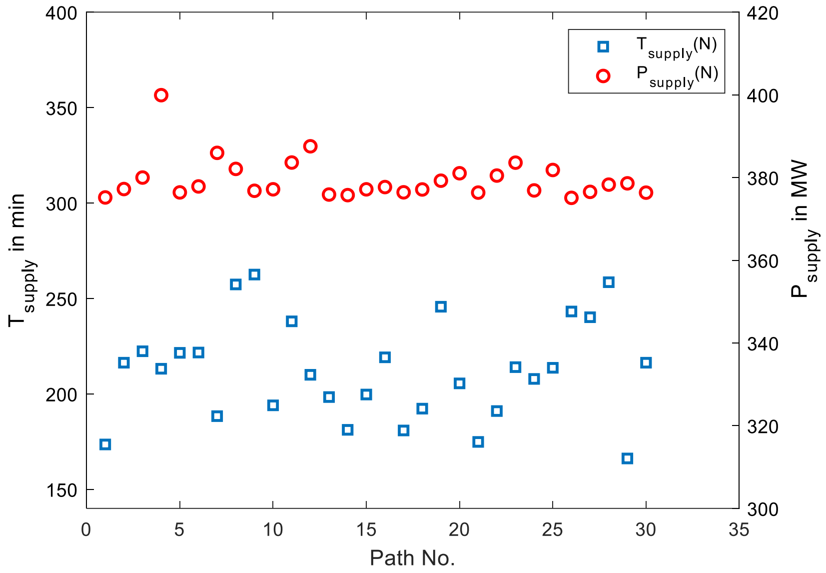


Figure 4: An overview of $T_{supply}$ and $P_{supply}$ for 30 paths

In Figure *5*, 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, as the rate of change of power supply of path No. 29 gets much bigger than path No. 9, hence 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 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 load is reconnected stepwise during the PSR process, generators' active power is adjusted correspondingly as shown in Figure 5.

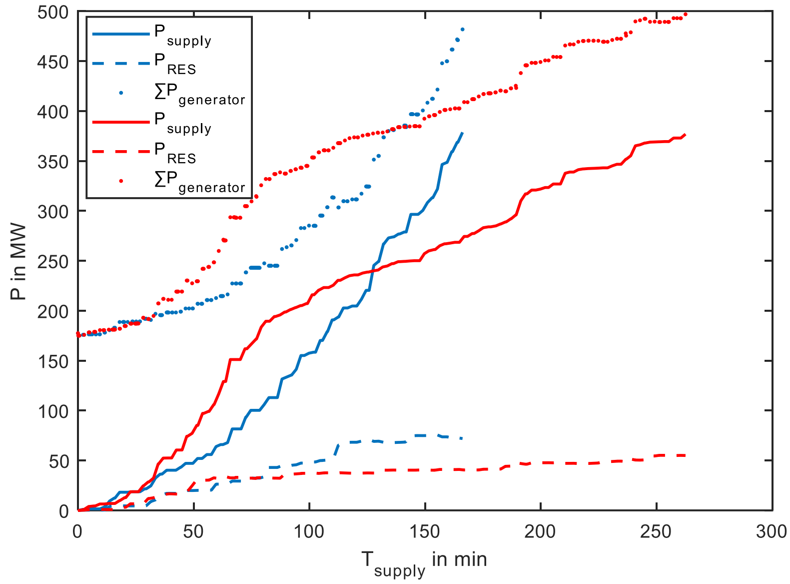


Figure 5: The comparison between path No. 29 (blue) and path No. 9 (red)

Regarding the average maximum load steps, the path No. 10 has the highest value of $\overline{\Delta P_{max-load}}$ 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 *6* shows an overview of $\Delta P_{max-load}$ and $\overline{\Delta P_{max-load}}$ for 30 paths.

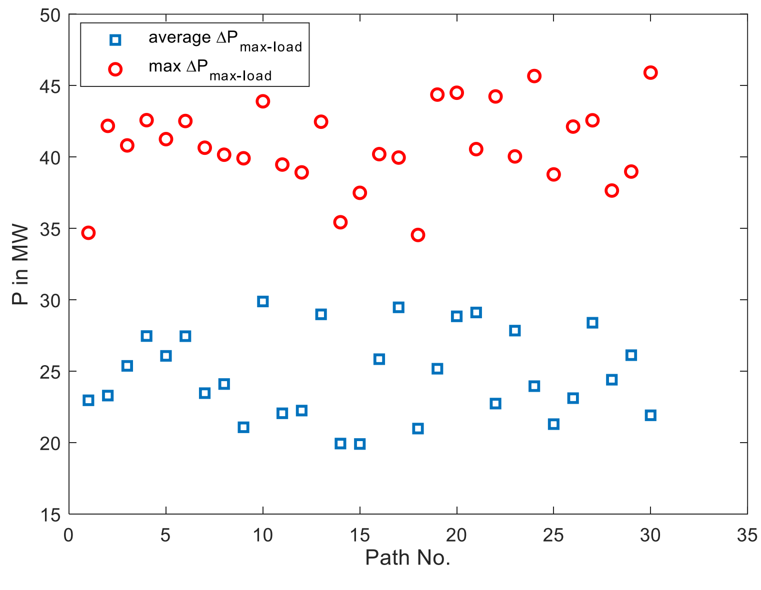


Figure 6: An overview of $\Delta P_{max-load}$ and $\overline{\Delta P_{max-load}}$ for 30 paths

Figure *7* 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 50% of system restoration between these two paths is 5.6 min. As shown in Table *1*, there is an 8 MW difference of active power reserve in the last step of both paths.

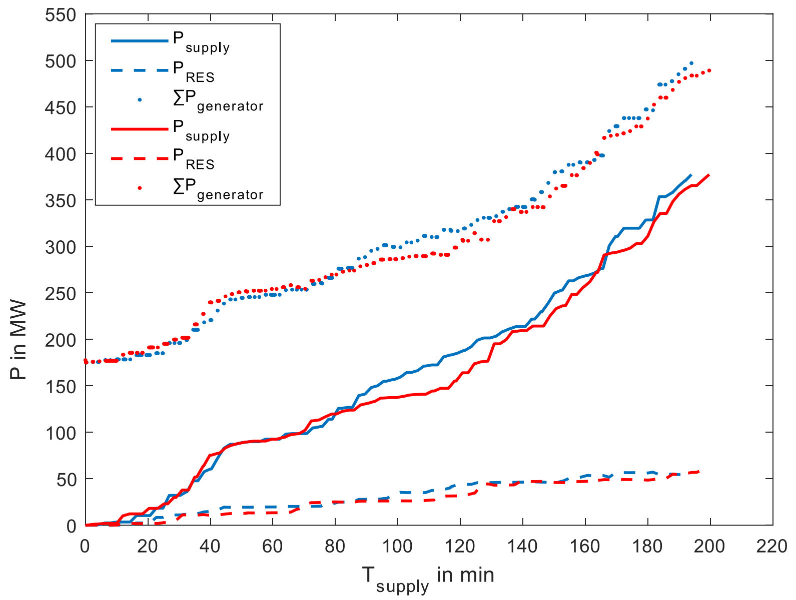


Figure 7: The comparison between path No. 10 (blue) and path No. 15 (red)

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 *8* shows the comparison of power reserve of all indicated paths.

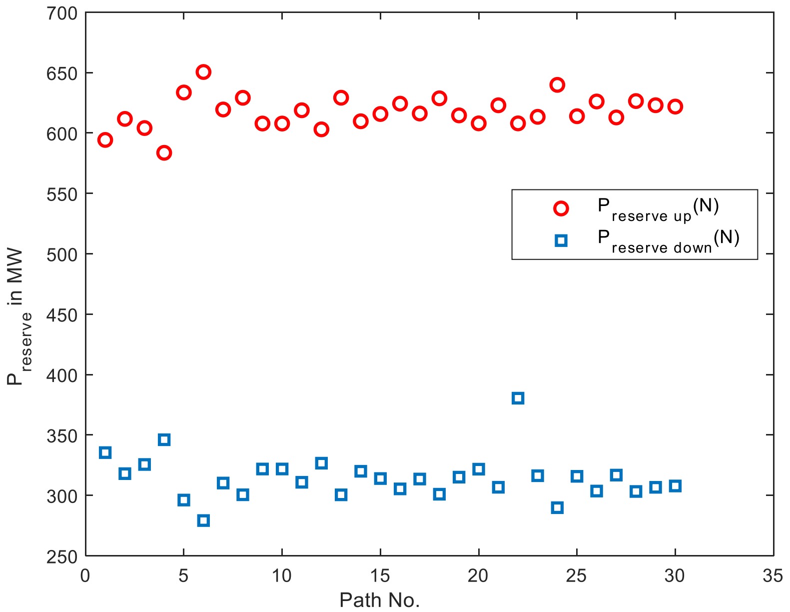


Figure 8: An overview of power reserve for 30 paths

Figure *9* shows the RES infeed and load power demand during the restoration process for both paths. Path No. 6 requires longer time 221 min for supply of 377.85 MW and shows a higher average load step ability during the restoration.

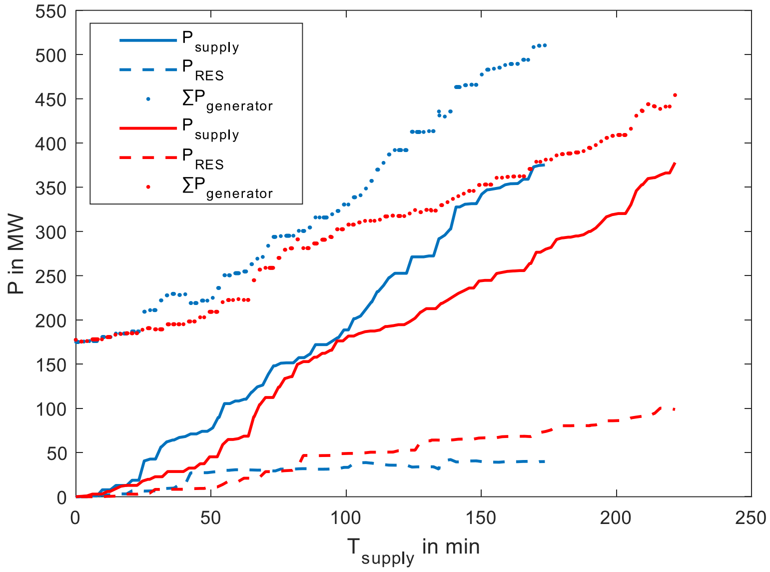


Figure 9: The comparison between path No. 1 (blue) and path No. 6 (red)

## 5 Conclusion and Outlook

Path identification algorithms, parallel BFS and oDFS based on Monte Carlo approach are developed and applied in this paper. The developed algorithms provide a fast computation on multiple processors and allow stable restoration for 50% of the total system load demand. Since parallel BFS is used to calculate up to level 3, it provides a bunch of different initial states for further calculation based on parallel oDFS, to be compared in terms of KPI selected to assess the generated restoration paths. By combining BFS and oDFS algorithms, 30 random and different paths that restore the real DSO 110 kV network with 158 buses were generated. For the system restoration, the Build-up strategy is applied, i.e. the system is restored from units within the system operated by the DSO.

The generated paths are presented and further investigated. The KPI relevant for the different paths are compared, in order to find more suitable approaches for system restoration. Significantly more of these random paths are planned to be generated based on the parallel BFS and oDFS algorithms at VSC. For future work, a combination of global and individual KPI based on certain weighting factors should be developed to evaluate paths, so that a more precise indication on the optimal PSR path can be given.

## 6 Acknowledgement

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