IMPACT OF RENEWABLE AND DISTRIBUTED GENERATION ON GRID RESTORATION STRATEGIES

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ABSTRACT

The research project RestoreGrid4RES aims to develop a concept for secure grid restoration after blackouts considering increased share of distributed generation and renewable generation sources. The volatile renewable generation sources generators as well as the cold load pickup bring significant challenges to network operation during a power system restoration. Especially automatic reconnection of distributed generation is a major threat for system frequency stability during grid restoration starting from small islands, when resynchronization takes place in an uncontrolled manner.

This paper focuses on i) the reconnection behavior of feeders with a high share of renewable generation sources and residential loads, ii) the description of strategies and key performance indicators for the assessment of grid restoration options and iii) the related theoretical framework.

INTRODUCTION

The increasing electricity trade and high share of distributed generation (DG) and renewable generation sources (RES) with limited controllability increase the probability of the occurrence of large grid outages known as blackouts. These Blackouts have serious consequences and can cause economic and societal losses. Furthermore, the volatility of DG and RES make the power system restoration (PSR) after a blackout more complex and bring additional challenges during the restoration process. Hence, the research project RestoreGrid4RES investigates more secure and reliable PSR methods considering abovementioned challenges.

This paper is divided into three parts. In the first part, based on the ENTSO-E definition, three new PSR concepts are developed and introduced to clarify the responsibility of distributed system operators (DSOs) [1] .

Secondly, long lasting power interruptions in medium voltage grids may cause an initial peak active power of load demand much higher than its previous value, which is known as cold load pickup (CLPU). In addition, a high share of DG and RES with automatic synchronization characteristics may lead to system frequency instability. Based on the acquired data from Austrian DSOs, namely KNG Kärnten Netz GmbH and Netz Oberösterreich GmbH, a model of a distributed network including load, DG and RES according to the relevant network codes is presented.

In the last part of this paper, the developed algorithms are introduced, which describe PSR strategies and key performance indicators (KPIs) together with an optimization algorithm to find the best path to restore the system based on a Monte Carlo tree.

STATE OF THE ART

Power system restoration strategies

PSR strategies are essential and have to be available for grid operators to re-energize the network in case of a blackout event. A review of existing PSR strategies in Continental Europe shows that they can be divided into several categories regarding coordinated actions and relationships between transmission system operators (TSOs), e.g. Top-down and Bottom-up strategies, as well as between TSOs and DSOs, e.g. the Build-down, Build-up and Build-together strategies.

Among them, currently only Top-down and Bottom-up are addressed in the ENTSO-E network code [1]. The Top-down strategy requires the assistance from neighboring TSOs to re-energize the system of a TSO, while the Bottom-up strategy requires no help from other TSOs, but uses own black start units (BSUs) to self-re-energize. Since the responsibility of DSOs during PSR is presently not described in the network code, Build-down, Build-up and Build-together strategies are introduced. Build-down means that there is no BSU available in the distribution network, thus, to re-energize the DSO network, the assistance of the upstream TSO is necessary. Build-together indicates that BSUs exist in both the transmission and distribution network, and hence the distributed network of the TSO and the DSO can be self-re-energized independently. Build-up strategy means that no BSU is available in the transmission network, but only in the distribution network. In this case, the disturbed system of a DSO is self-re-energized and supports restoration of its upstream TSO. The utilization of these five strategies either solely or being combined should be decided by the involved network operators depending on the actual situation [2].

Scenario 2025

Based on the provided data by Austrian DSOs, to investigate CLPU as well as the resynchronization behavior of DG and RES, a distribution network model is developed and depicted in Figure *1*. It has two voltage levels, namely 30 kV and 110 kV. The main components are a lumped load with the power consumption of 20 MW, a 6.9 MW photovoltaic generator (PV), a 0.2 MW wind turbine generator (WT), three transformers and a synchronous generator using the speed governor model TGOV1 [3]. The aggregated load model accurately represents CLPU with the overload factor of 2.5 [4], and the behavior of PV and wind generation follows the VDE 4110-AR-N standard in the medium voltage level [5].

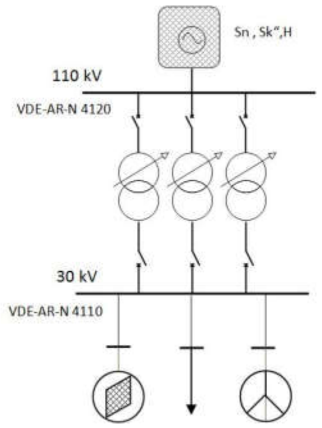

Figure 1: Distributed network model

Based on the estimated values provided by Netz Oberösterreich GmbH, the increase of the capacity of installed PV is scaled by +150% and that of wind generation by +10% for the year 2025. The PV and WT resynchronization behavior, CLPU and network frequency are depicted in Figure *2* for both scenarios 2017 and 2025. The red line stands for scenario 2017 and the green line represents scenario 2025.

MODEL DEVELOPMENT

The PSR models represent residential loads with CLPU effect, PV converters with their synchronization and start-up behaviors, 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 seen on 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 behavior. 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 behaviors and those which remain in stand-by modus at re-energization. These models are explained in details in [6].

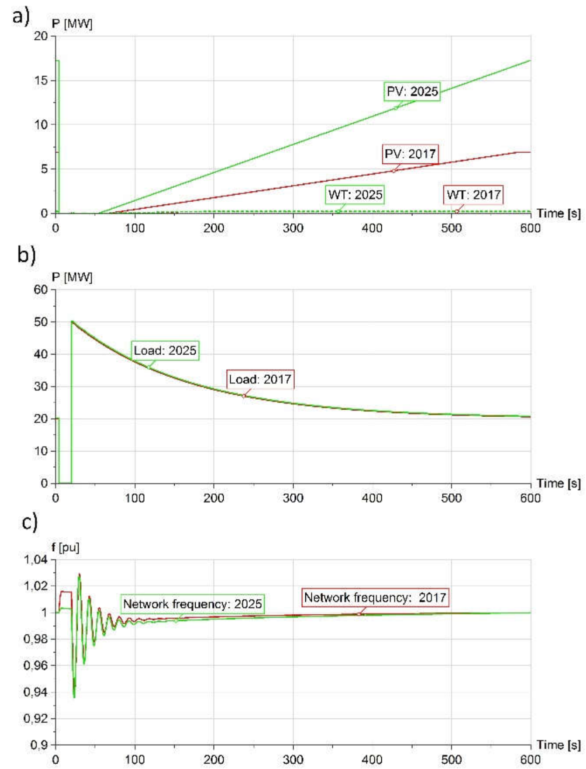

Figure 2: a) resynchronization behaviour of PV and WT b) Cold load pickup c) Network frequency for scenario 2017 and 2025

The PV-inverter model reflects the resynchronization and startup behaviors 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 behavior 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 any EVs are in charging mode exactly at the power interruption time instant, they will continue their charging process at the time of re-energization. If the charging of any 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 4 hours in a working day in the summer of 2022 is illustrated in Figure ***3***. The aggregation consists of a network group with 100 households each having 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.

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 gets mainly charged at around 9:00 as the residual load has a negative value. When the power interruption starts at 10:00 o'clock, the residual power becomes zero and the BESS starts to discharge due to its self-discharging effect. By the re-energization at 14:00, the battery kicks in immediately covering 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 is observable by the power spike at 14:00 o'clock in the residual load with a red solid line. As the PV generators kick-in a few minutes after the re-energization time instant, the residual load becomes negative again and the BESS gets charged once more. The BESS gets fully discharged at around 17:00 and the red solid line returns to the residual load curve. The BESS is practically involved in the PSR from the beginning of the re-energization for a duration of 3 hours. This results in an almost zero residual load in this interval which is seen from the external grid.

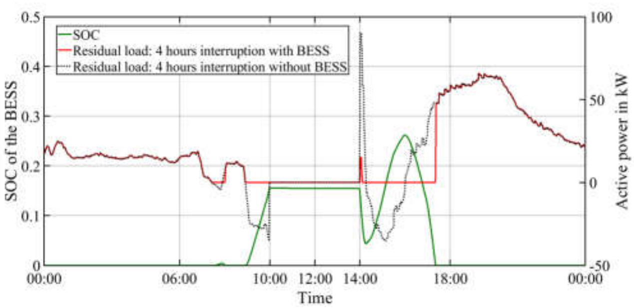

Figure 3: PSR model aggregation for a 4-hour power interruption with BESS details

The aggregations of the models for different outage durations without the BESS are plotted in Figure *4*. The black line indicates the residual power in normal operation while the colored curves are ones with interruptions at 10:00 o'clock with interruption durations from 1 to 10 hours. Apparently "ping-pong" effects are observable which are caused by the CLPUs and the belated PV inverter re-synchronizations.

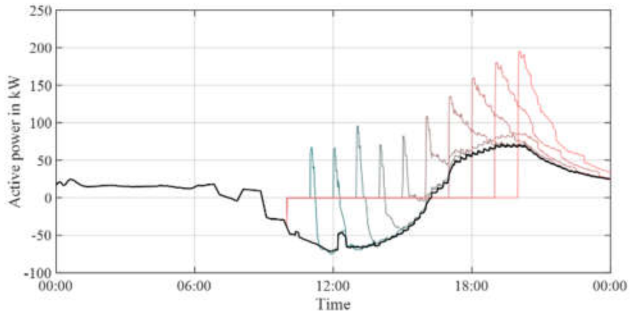

Figure 4: PSR model aggregation for a 4-hour power interruption without BESS details.

IDENTIFYING OPTIMAL POWER SYSTEM RESTORATION STRATEGIES

In this section, the related theoretical framework for identifying optimal PSR strategies under the presence of RES is investigated.

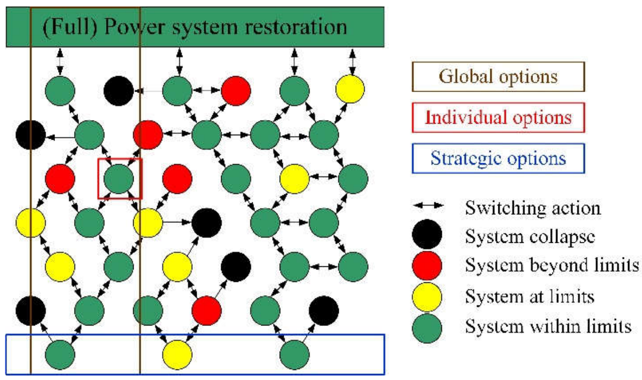

Figure 5: Possible restoration paths[1]

Possible PSR paths are depicted in **Figure 5**. As a first step, grid data and parameters are determined and loaded into the simulation system. Furthermore, possible starting points, which are defined by choices for strategic options and individual circumstances related to the blackout, have to be determined. The strategic options include boundary conditions, influencing parameters and decisions to be made. These decisions define, for example, basic PSR strategy, start-up frequency and maximum load and generation to be re-connected. Via specific actions, e.g. switching of lines and change of set points, the state of the system can be changed from one to another. The MATLAB code of the simulation system executes one

[1] The highlighted global option represents only a selection of possible paths starting from the second strategic option

possible action after the other and calculates the new network state(s).

If the system's physical values based on a load flow calculation are within the critical limits after these actions, they will be stored as zero up to n possible actions following the previous system state.

Identification of possible paths

To develop, compare and benchmark different PSR strategies all potential PSR processes (global options) are modelled as a very large tree-like directed acyclic graph. The goal is 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, the probability to find valid paths through the graph is increased by using a method based on Monte Carlo tree search, an external database (MySQL) with optimized storage strategies and distributed computing.

A node represents a network state and the arrows are (switching- or other) actions. In the algorithm, a node from the database is selected randomly through a Python file and inserted into a MATLAB file, as depicted in Figure 6. After the load flow calculation carried out in MATLAB, the children nodes of the chosen node are sent back to the Python script. All new nodes are then stored in the MySQL database, including the relation of parent and children nodes.

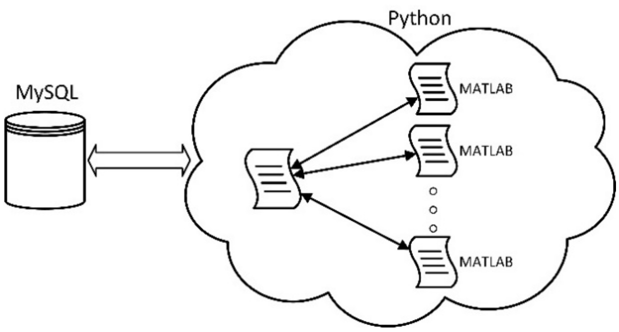

Figure 6: Conversation between components

In **Figure** *7*, the proposed algorithm is represented by a flow diagram.In order to speed up the computation times, this is done in parallel by several compute accounts (cores), where the same MATLAB script is running. Open message passing interface (MPI) for Python parallelizes the access to the database and the performance of the different accounts. In addition, the resources of a high performance computer and a temporary SQLite database in the workspace are used.

If necessary, to speed up the calculation time, the tree structure can be shortened and simplified. For example, system restoration can be defined to be reached when only 50% of the load are supplied, as from then on, the individual actions of the operator are no longer extremely sensitive because the system is more stable. Similarly, instead of switching each individual line, the network can be energized and switched in blocks. Further simplifications can be made with loads. This can be done through switching all the related components, e.g. lines and transformers, at once instead of one by one.

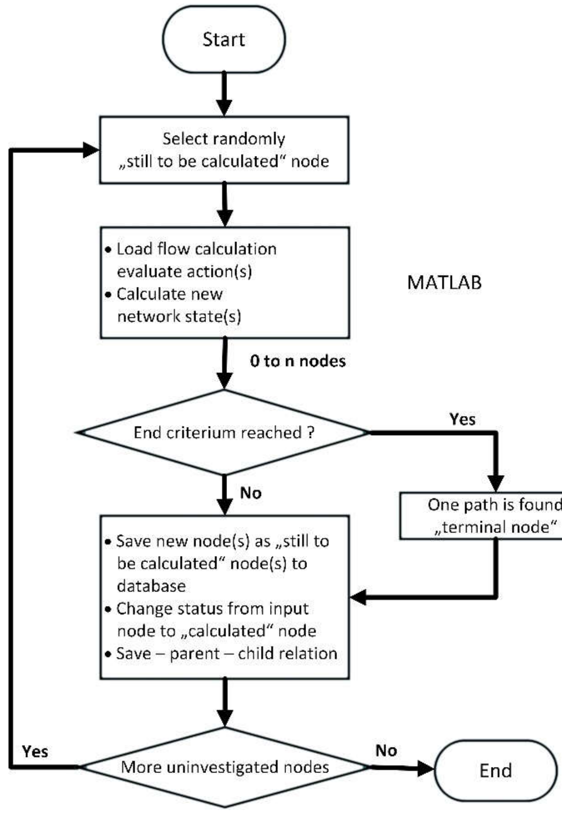

Figure 7: Flow diagram of the proposed algorithm

Key Performance Indicator

The green lines in Figure 8 show two possible paths to full energy supply. These paths are calculated in system model. Global and individual KPIs are defined to benchmark the PSR process after improvement is efficient, reliable and secure or not. Global KPIs consider the overall restoration process, while individual KPIs are valid only for a specific state occurring during the system restoration.

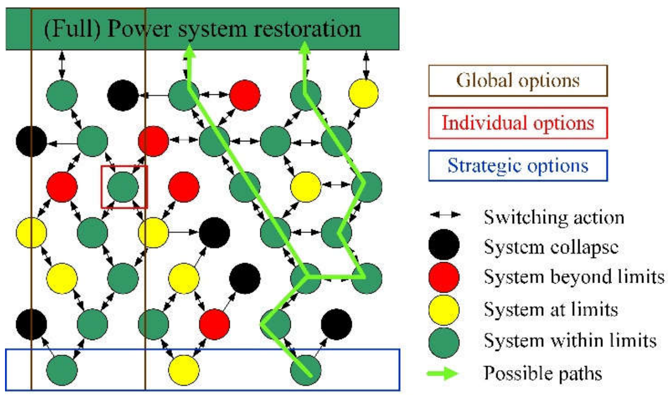

Figure 8: Possible restoration paths and KPIs evaluation

Time to a full system restoration (T_{FSR}), energy to be provided during the entire process (E_{FSR}), maximum voltage and frequency deviation as well as the integrals of voltage and frequency deviation over the restoration time are referred to as global KPIs. For a better understanding, some equations of these global KPIs are illustrated as followed. The E_{FSR} is presented in Equation (1):

$$E_{FSR} = \int_0^{T_{FSR}} P_{system}(t)dt \qquad (1)$$

where $P_{system}(t)$ is the total system load.
The integral of voltage and frequency deviations over entire restoration time ($\Delta v_{max,int}$ and $\Delta f_{max,int}$) are calculated as:

$$\Delta v_{max,int} = \frac{\int_0^{T_{FSR}} \max_i |v_i(t)-1| dt}{T_{FSR}} \qquad (2)$$

$$\Delta f_{max,int} = \frac{\int_0^{T_{FSR}} max|f(t)-f_0| dt}{T_{FSR}} \qquad (3)$$

The number of nodes in the system is represented by i and $v_i(t)$ means the time characteristic of the voltage of each node over the system restoration time in p.u. whereas $f(t)$ and f_0 are the actual system frequency and the nominal frequency.
Individual KPIs include system size, inertia, power reserve, system load step ability, number of possible paths to system restoration, number of good switching options and robustness against possible contingencies during 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 KPIs, the relevant network restoration strategies are then allocated.

CONCLUSION

This paper investigates the cold load pickup behavior as well as the gradual resynchronization and increasing power infeed of DG and RES, which can have a destabilizing effect on the system restoration process. The repeated connection and disconnection of DG and lack of control over power infeed may cause frequency instability problems. Moreover, a "ping-pong" effect, which is caused by the CLPUs and the belated PV inverter re-synchronizations is shown.
Furthermore, a developed algorithm is presented, which describes the reviewed and newly introduced PSR strategies and KPIs together with an optimization algorithm to find best path to restore the grid based on the Monte Carlo tree search and a database with optimized storage strategies and distributed computing. For assessing the system restoration process, global and individual KPIs are defined, to check whether the restoration process after optimization is efficient, reliable and secure or not.
At the last stage of the RestoreGrid4RES, an innovative tool shall be developed to guide grid operators during the PSR process.

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