# An iterative approach to grid topology and redispatch optimization in congestion management

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*Abstract*— **The selection of Remedial Actions (RA) to ensure system security is a highly complex task performed by Transmission System Operators (TSOs). Phase shifting transformer (PST) tap changes and active power changes of generation units (redispatch) are some RA available in Security Constrained Optimal Power Flow (SCOPF) simulations within the operational planning processes. Topological RA are not part of these SCOPF yet, as the optimization thereof adds high complexity to the existing optimization problem. To overcome this complexity, this paper introduces an iterative approach that decouples topology optimization from redispatch & PST optimization. Linearized models of RA are used to meet computation time requirements. Exemplary investigations of the presented method were performed based on modified IEEE 39-Bus, 118-Bus and PEGASE-1354-Bus grid models. Within the scope of these investigations, the method shows good results and a great potential for the reduction of congestions and required redispatch through topological RA. In order to eliminate inaccuracies of the approach and to further improve its suitability for use in grid operation, a need for future investigations and possible further developments were identified.**

***Index Terms--Approximation algorithms, Linearized Models, Redispatch Optimization, Topology Optimization***

## I. INTRODUCTION

Energy policy developments in recent years have led to a significant transformation of the energy sector. As part of this transformation, the need for energy transportation is increasing due to the expansion of distributed generation, the decommissioning of conventional power plants, and the rise in international trade. Overall, the resulting increase in the geographical distance between generation and load leads to higher grid loads and consequently to congestions. Grid expansion will be necessary to meet the changing transport requirements. However, since grid expansion is a long-term task, the short-term congestion management has gained in importance. [1]

Grid congestion is defined as the exceeding of the operational limits of a grid element. These operational limits include thermal limits, voltage, and stability requirements, with thermal limits of transmission lines being the most commonly considered factor in determining transmission capacity. [2] In addition to the physical limits, safety margins are considered to cope for uncertainties of the forecasts used in grid operation. Of particular note is the consideration of grid security in the event of a grid element failure under the N-1 criterion. [3] According to this criterion, the operational security limits must still be maintained in the N-1 case. To comply with these operational security requirements, TSOs apply Remedial Actions (RA) as part of their congestion management. [1]

The EU policy for coordinated operational planning foresees the definition of RA preferably in day-ahead or two-day-ahead processes [4]. Available options in the short term comprise adaptions of the grid topology as well as adaptions of generations and loads (Redispatch). Switching operations can be used to reconfigure the grid and influence the power flows. Cancelation or delay of planned outages for maintenance, is another option in congestion management. In addition, power flow management resources such as PSTs and flexible alternating current transmission systems (FACTs) can be used. [1]

According to the System Operations Guideline, TSOs shall select and activate the most effective and economically efficient RA. The activation should be as close to real time as possible, considering the expected activation times and urgency, as well as the risks of activation failure and the possible impact on the operational security. [5] From the point of view of economic efficiency, topological RA have the advantage that their marginal costs are so low that they are generally referred to as non-costly. [2] Whereas costly RA include measures, that involve interventions in the market (e.g., Redispatch) and lead, to compensation payments and the operation of power plants with higher marginal costs. [3, 6] Therefore, activation of non-costly topological RA instead of other costly RA should be taken into consideration as a preferred option for congestion management. Consequently, both types of RA should be considered in procedures for Remedial Actions Optimization (RAO). This paper presents a possible approach that considers the existing time constraints in short-term congestion management. Linearized models of RA are used to meet the computational time requirements. A decoupled optimization of the grid topology as well as the redispatch and PSTs is performed to reduce the complexity of the problem. The suitability of the approach with a focus on a possible reduction of the redispatch demand and the computation times is examined in the context of exemplary results.

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## II. PROBLEM ANALYSIS

The use in congestion management places a variety of requirements on the optimization methods to be adopted. An important requirement is the limitation of the computation time, due to the short-term nature of congestion management processes. As an example, the Day-Ahead Congestion Forecast (DACF) process, that is currently in operation in intercontinental Europe, specifies a process start at approximately 5 p.m. after the day-ahead market results are available and power plant schedules have been reviewed. [7] The operational congestion management, carried out by the TSOs as part of this process, is supposed to identify suitable RA for the next day, starting at 0:00 AM. Considering that it is a multi-step process that requires a high level of coordination between TSOs, as well as collecting and merging large amounts of data and performing grid calculations, the available computation time for the RAO is only a fraction of the process time. [8] This makes computation time a significant limiting factor in the selection of a suitable optimization procedure.

Methods for the optimization of congestion management measures are usually based on Optimal Power Flow (OPF) calculations. The underlying optimization task is a nonlinear and nonconvex optimization problem (AC-OPF) due to the interrelationships in the complex three-phase power system. The additional mapping of topological RA by binary state variables leads to a complex combinatorial optimization problem. Solving such problems for real grids is not possible in acceptable computation time. Consequently, current approaches are usually based on heuristics. Possible concepts that have been investigated in existing research are presented in the following section. [9, 10]

## III. STATE OF RESEARCH

Topology optimization has been the focal point of much research in the field of grid operational planning and grid expansion planning. Due to the increasing importance of congestion management within TSO processes, many different approaches to topology optimization have been investigated. In the following, the most important approaches that have been investigated in a large number of publications are presented.

### Metaheuristic Approaches

Metaheuristic methods are suitable for solving various types of optimization problems, including nonconvex and nonlinear optimization problems. Metaheuristic approaches do not require information about the optimization problem. All necessary information is taken from candidate solutions. Thus, separate computational methods such as power flow calculations can be used without explicit modeling in the optimization problem, making metaheuristics well suited for solving complex problems like topology optimization. [8, 9] Possible approaches using particle swarm optimization as a metaheuristic method were shown in Moormann et. al (2015) [11] and Scheel (2018) [12]. Another example is the method presented by Kaptue Kamga (2009), which uses genetic algorithms. [10] A major drawback of metaheuristics is that there is no guarantee that a solution with sufficient solution quality will be found in a short computation time. Therefore, their application in time-critical processes of transmission system operation is questionable. [9, 13]

### Artificial Intelligence

As artificial intelligence (AI) methods continue to be better researched and developed, their fields of application are steadily increasing. In recent years, various approaches from AI have also been explored for grid topology optimization. Approaches aim to optimize topology by means of Reinforcement learning (RL). One concept using an actor-critic algorithm has been presented by Yoon et al. (2021) [14]. Another recent approach presented by Dorfer et al. (2022) [15] uses RL methods to optimize either topology or redispatch, and additionally presents a two-step approach for subsequent optimization of topology and redispatch. Since these approaches consider either topology or redispatch optimization only, or two-stage approaches without direct consideration of the interactions between redispatch and topology measures, the full potential of the measures is not yet realized.

### DC power flow approximations

To simplify the topology optimization problem, a DC power flow can be used as an approximation for the complex AC power flow. Thereby, the power flow can be described as a linear system of equations. Consequently, the DC OPF problem is a convex optimization problem. To optimize the grid topology, the problem can be extended to include binary switching variables, resulting in a mixed integer linear program (MILP). An exact solving of such problems is possible but can lead to long computation times for real transmission grids. [9] An example for the use of DC formulations to optimize grid topology under consideration of the grid security has been presented by K Hedmann (2009) [16]. Since this is an NP-hard problem, the solution is complicated and time consuming. However, heuristics can be applied to enable faster computation. [16] A remaining drawback of the DC formulation is that voltage magnitudes and reactive power flows are not considered. Furthermore, the results obtained show deviations of up to 10% from the complex power flow. [9, 17]

### System Deflection

System Deflection modelling methods have been developed, to provide more accurate results without the necessity of repeated power flow calculations. [17] For this purpose, the power flow equations are linearized around an operating point. These equations can be solved for a deflection from the operating point, for example due to changes in the grid topology or load and infeed. [18] Such approximations are commonly used for contingency analysis or the formulation of optimization problems, as effects of Outages and RA can be represented by linear sensitivity factors. [17] An efficient approximation methodology for topological RA has been proposed by Eickmann et al. (2014) [17]. One procedure for optimizing RA for congestion management using this methodology was presented by Eickmann (2015) [18]. In this procedure the grid topology is first optimized and then the redispatch is determined based on this topology. Thus, interactions between redispatch and grid topology cannot be represented. Schedule changes due to redispatch can result in the initially determined topology no longer being optimal. To overcome this problem, iterative approaches can be useful. One such approach was presented by Hoffrichter (2020) [19].

One difficulty with optimization based on linear sensitivity factors, are the interactions between RA. For example, topological RA can significantly influence the effectiveness of redispatch. A simple superposition of the linear sensitivity factors can lead to larger deviations due to the increasing deflection from the operating point. Therefore, targeted recalculations of power flow and sensitivities are useful in iterative approaches. On the other hand, due to the large number of degrees of freedom, methods for complexity reduction are also necessary for these methods. It is therefore necessary to find a good tradeoff between accuracy and computation time. One possible approach to cope with these difficulties is the subject of this paper.

## IV. METHODOLOGY

To meet the computation time requirements within the TSO processes, various simplifications of the power flow calculations and optimization procedures are necessary within the presented methodology. Thus, the use of linear sensitivities is foreseen to model redispatch and PST taps. Outage situations and adaptions of the grid topology can be modeled by means of the power injection method. Furthermore, a pre-selection of reasonable topological RA is used as input data, limiting the degrees of freedom of the topology optimization. Moreover, the optimization problem is divided into two separate optimization steps (figure 1). The first step identifies suitable topological RA. In a second step, a SCOPF is performed to determine redispatch and PST taps. Thus, the size of the optimization problem is reduced. In addition, power flows and linear sensitivities are recalculated in between optimization steps to allow a reassessment of the grid situation after application of selected RA. Since the grid topology affects the sensitivities of power plants and PSTs and vice versa, this approach ensures accurate calculation of the sensitivities of these RA in each optimization step. In the end, this iterative approach enables a stepwise alignment of optimized changes of the topological RA and further RA determined during the SCOPF (redispatch and PST taps).

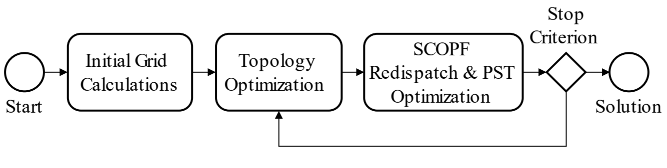

Figure 1. Process Flow

**Sensitivity Calculation (System Deflection Modelling)**

Sensitivity calculations allow the approximation of power flow changes caused by small adaptions in the grid, like adapting load and infeed or minor topology changes. For this purpose, the power flow equations are linearized around the initial operating point using the inverse Jacobian matrix $J^{-1}$ (formula 1). [18, 20]

$$\begin{pmatrix} \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \\ \frac{\partial \theta}{\partial P} & \frac{\partial \theta}{\partial Q} \end{pmatrix} \cdot \begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \mathbf{J}^{-1} \cdot \vec{S}^{inj} \tag{1}$$

Changes in the load and infeed situation can be represented by an adjustment of the node balances. [18] Therefore, a power injection $\vec{S}^{inj}$ is performed on the initial Jacobian Matrix. The resulting node voltages can be calculated by superimposing the initial voltage values and the voltage delta caused by the power injection (formula 1). Subsequently the resulting branch currents can be calculated based on the new voltages according to formula 2.

$$\vec{\underline{I}} = \underline{Y} \cdot \vec{\underline{U}} \tag{2}$$

Adjustments of the grid topology as well as element failures, on the other hand, can be modeled by an adjustment of the admittance matrix and current/power injections. [17, 18] The power injection is used to model the change in grid topology. By superposition, the system state can be approximated after adjusting the topology, as shown in Figure 2 for the example of an outage.

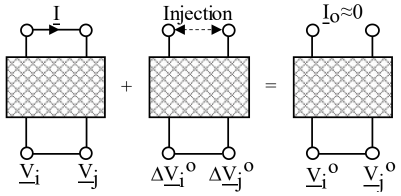

Figure 2. Power Injection and Superposition Approach

The System Deflection Modelling has been extended by Eickmann et al. (2014) [17] to incorporate efficient approximations for topology optimization approaches. Based on the extended methodology fundamental topological switching actions (figure 3) are modeled and optimized in this paper. The approximations used, as well as an extension for modeling busbar switching, are briefly presented below.

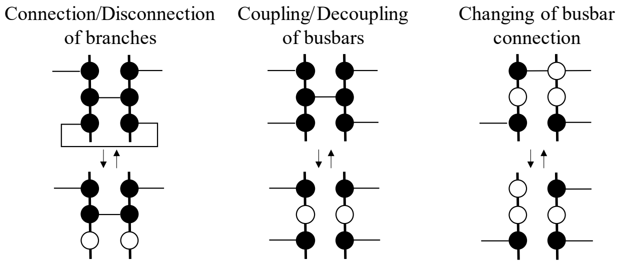

Figure 3. Fundamental Topological Swichting Actions

### A. *Disconnection of Branches/Opening of Busbar Couplers*

In the presented procedure, the couplers are modeled as electrically short branches with low impedance. Consequently, the opening of couplers and disconnection of branches can be modeled in the same way as an outage. Since it is known that the power flow over the opened branch is zero, a power injection can be performed at the connecting nodes, which simulates a reverse power flow. The injection is performed based on the grid topology considering the opened branch by adapting the admittance matrix and the Jacobian matrix. The resulting power flows on all branches can be approximated by superposition of the initial state and the result of the power injection. [17]

### B. *Closing of Busbar Couplers*

In contrast to the closing of busbar couplers, when opening a busbar coupler (figure 4), it is not known at first which power flow will occur on the coupler after the switching action. Consequently, this power flow must first be determined. For this purpose, it is assumed that the assumption (3) applies to the voltage at the connection nodes.

$$\underline{V}_{i1}=\underline{V}_{i2} \tag{3}$$

The resulting current flow must therefore compensate for the voltage drop across the open coupler. Consequently, the current flow over the coupler can be calculated according to equation (4).

$$\underline{I}_S=\frac{1}{\sqrt{3}}\cdot\frac{\underline{V}_{i1}{}^0-\underline{V}_{i2}{}^0}{\underline{Z}_{grid}{}^{i1,i2}} \tag{4}$$

Based on the current, the power injections can be calculated based on equations (5) and (6).

$$\underline{S}_{i1}{}^{inj}=-\sqrt{3}\cdot\underline{V}_{i1}{}^0\cdot\underline{I}_S{}^* \tag{5}$$

$$\underline{S}_{i2}{}^{inj}=\sqrt{3}\cdot\underline{V}_{i2}{}^0\cdot\underline{I}_S{}^* \tag{6}$$

For a more precise derivation, reference can be made to source Eickmann et al. (2014) [17].

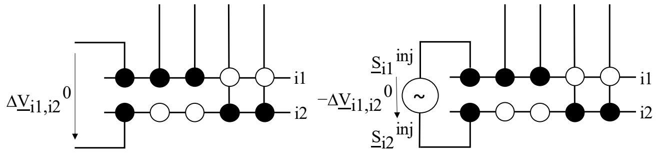

Figure 4. Busbar Closing Model [17]

### C. *Connection of Branches*

In contrast to closing of busbar couplers, connecting branches results in a voltage drop across the branch. Consequently, the voltages at the connection nodes j and i are not identical and equation (3) does not hold. Thus, both voltages and current after switching are unknown. To overcome this problem, Eickmann et al. (2014) [17] introduces an approach that extends the grid model by an auxiliary node $j_2$. This node becomes the connecting node for the branch b (figure 5).

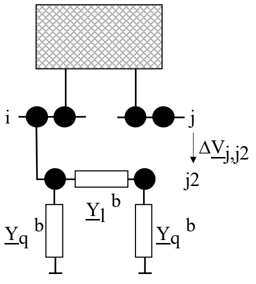

Figure 5. Branch Connection Model [17]

To incorporate the new auxiliary node into the grid model, the admittance matrix and Jacobian matrix have to be extended. Then, the voltage at the auxiliary node can be calculated according to equation (7) using the quadripole parameters of the new branch, assuming that the influence of the new branch on the voltage at node i is negligible. [17]

$$\underline{V}_{i1}=\frac{\underline{Y}_{21}{}^b}{\underline{Y}_{22}{}^b}\cdot\underline{V}_i{}^0 \tag{7}$$

Subsequently, the branch current can be calculated based on equation (8).

$$\underline{I}_S=\frac{1}{\sqrt{3}}\cdot\frac{\underline{V}_{j2}{}^0-\underline{V}_j{}^0}{\underline{Z}_{grid}{}^{j,j2}} \tag{8}$$

Equivalent to the closing of busbar couplers, the power injections can be calculated based on the current as described in equation (9) and (10).

$$\underline{S}_{j2}{}^{inj}=-\sqrt{3}\cdot\underline{V}_{j2}{}^0\cdot\underline{I}_S{}^* \tag{9}$$

$$\underline{S}_j{}^{inj}=\sqrt{3}\cdot\underline{V}_j{}^0\cdot\underline{I}_S{}^* \tag{10}$$

A detailed description of the matrix extensions necessary for the power injection can be found in Eickmann et al. (2014) [17].

### D. *Adaption of Busbar Connections*

The adaption of the busbar connection of branches is modeled by a two-step approach, which consists of the previously described steps of Disconnection of Branches and Connection of Branches as displayed in figure 6.

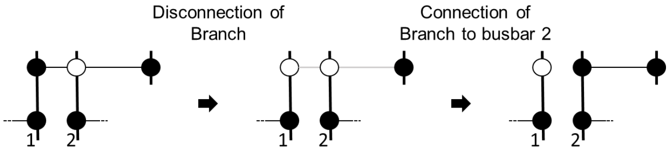

Figure 6. Busbar Switching Model

First the branch is disconnected to approximate node voltages in the grid. Therefore, the branch is removed from the grid model, by adjusting the admittance and Jacobian matrices. Subsequently the branch can be connected to the new busbar by following the steps described for connecting a branch, based on the adjusted grid topology and voltages.

**Optimization Problem**

The iterative optimization procedure consists of two separate optimization problems. The first optimization problem is built for the topology optimization. The second optimization problem is built for solving the security constrained optimal power flow. Since SCOPF formulations have been described frequently in literature, a detailed description of the optimization problem is omitted here. Information on applications and formulations of the SCOPF can be found in [21] and [22].

The topology optimization aims to identify suitable topological RA that relieve congestions in the grid. For this purpose, a cost-based objective function is used to minimize the total penalty cost of branch congestion in terms of branch slack and cost of implementing topological measures. Considering the optimization variables (Table 1) and the optimization constants (Table 2), the objective function can be defined as follows:

$$\sum_b^B \Delta I_{b,slack} \cdot c_{b,slack} + \Delta I_{b,slack}^{N\text{-}1} \cdot c_{b,slack}^{N\text{-}1} + \sum_i^I \partial_i \cdot c_{topology} \quad (11)$$

TABLE I. TOPOLOGY OPTIMIZATION VARIABLES

| Variable | Description |
|---|---|
| $\partial_i \in \underset{\forall B}{\{0;1\}} \forall I$ | Decision variable for topological RA |
| $\Delta I_{b,slack} \ \forall B$ | Slack variables for branch current limits N-0 |
| $I_{b,slack}^{N\text{-}1} \ \forall B$ | Slack variables for branch current limits N-1 |

TABLE II. TOPOLOGY OPTIMIZATION CONSTANTS

| Constant | Description |
|---|---|
| $dI_{i,b}$ | Current delta cause by topological RA i on branch b |
| $dI_{o,i,b}$ | Current delta cause by outage o and RA i on branch b |
| $I_b$ | Initial branch current |
| $I_b^{N\text{-}1}$ | Initial N-1 branch current |
| $I_{b,max}$ | Branch current limit |
| $\partial_{max}$ | Topology RA limit |
| $c_{b,slack}$ | Costs for using branch slack N-0 |
| $c_{b,slack}^{N\text{-}1}$ | Costs for using branch slack N-1 |
| $c_{topology}$ | Costs for implementing topological RA |

The objective function that needs to be optimized is subject to the following constraints:

- Branch current limit N-0

$$\left|\underline{I}_b\right| + \sum_i^I \partial_i \cdot dI_{i,b} - \Delta I_{b,slack} \leq I_{b,max} \quad (12)$$

- Branch current limit N-1

$$\left|\underline{I}_b{}^{N\text{-}1}\right| + \sum_i^I \partial_i \cdot dI_{i,b} - \Delta I_{b,slack} \leq I_{b,max} \quad (13)$$

- Topological RA limit

$$\sum_i^I \partial_i \leq \partial_{max} \quad (14)$$

## V. EXEMPLARY RESULTS

Various aspects of the presented optimization approach are examined using a range of grid models. First, the effectiveness of the approach for reducing congestion and redispatch volume is examined using modified IEEE 39-Bus and 118-Bus grid models[1]. The suitability of the approach for application to larger grids was then investigated using a modified version of the 1354-Bus PEGASE grid model[1] [23] which is included in MATPOWER version 7.1 [24, 25].

For the investigations, the costs of topological RA in the objective function were parameterized based on studies of the accuracy of sensitivities. Thus, they should consider that the minimum effectiveness should be higher, if possible, than the usual linearization error of the sensitivity calculation. For application in real grids, additional factors need to be considered in determining the costs. In addition, the iteration limit for repeated topology optimizations was set to 3 iterations, to prevent cyclic switching. After the first 3 iterations, topology is fixed and only PSTs and redispatch are further optimized.

**IEEE 39- & 118-Bus Grid**

The grid models were modified to incorporate double busbars and busbar couplers. In addition, more lines were added to the grid models to achieve a higher degree of meshing. Furthermore, synthetic system use cases (SUCs) were created for each grid to represent many different power flow situations. A total of 1500 SUCs were considered. Thus, there are many situations in which the use of topological RA to reduce congestion is practical. The maximum applicable topology RA limit was set to 3, due to the small grid sizes. Up to 3 individual topological switching actions could be selected from a predefined set of fundamental switching actions. The set consisted of 14 RAs in the 39-Bus grid and 33 RAs in the 118-Bus grid.

### A. *IEEE 39-Bus Grid*

Applying topology optimization to the IEEE 39-Bus grid model results in an adaption of the grid topology in 780 of the 1000 synthetic SUCs considered. In 754 (96.7%) cases, the applied topological RA cause a reduction of the redispatch demand. In the remaining 23 (2.9%) cases, the demand increases. A maximum redispatch demand of 1223 MW occurred in the SUCs considered. The distribution of the achieved redispatch changes is shown in the histogram in figure 7.

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[1] Available at: https://github.com/Andreaewers/Grid-Model-Library

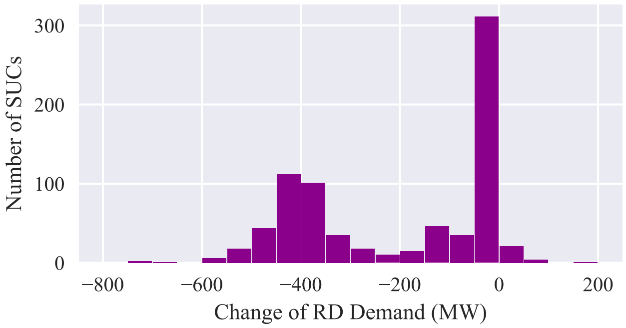

Figure 7. IEEE 39: Change of the redispatch demand

In the majority of cases (75.4%), the topology optimization shows great potential for reducing the necessary redispatch and only leads to an increase in redispatch in a few cases (2.3%). These cases are examined in more detail in order to determine the reasons for the increase.

The detailed analysis has shown that only in one case the congestion was increased by the topology optimization, which may be due to linearization errors in the sensitivities. As sensitivities are also determined for individual fundamental topological switching actions, the effects may deviate from the approximation in the case of combinations of remedial actions due to reciprocal effects. In the other cases, a reduction of the congestion was achieved by the topological RA and yet the redispatch demand was increased. To illustrate this, the total congestion of the grid can be expressed as bottleneck power. The bottleneck power is the sum of all overloads above its rated power, whereby the overload is specified in MW. The bottleneck power for the N-1-case before and after the first iteration of the topology optimization is displayed in figure 8.

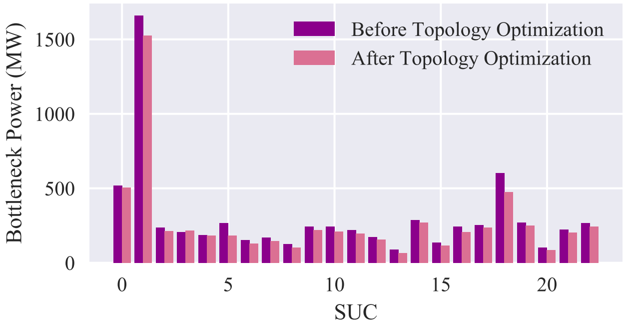

Figure 8. IEEE 39: Bottleneckpower before and after 1. topology adjustment

These observations are a consequence of the decoupled optimization of topology and redispatch. In topology optimization, available redispatch potentials as well as the effect of redispatches on overloaded branches are not taken into account. Optimization is performed exclusively with the goal of reducing the total bottleneck power. Therefore, topological RA can further overload certain branches if other branches are relieved more strongly as a result. If subsequently little effective redispatch measures are available for the remaining overloads, the redispatch demand may increase as a consequence. In order to avoid this behavior, further investigations will be carried out in the future and the procedure will be further developed accordingly.

## *B. IEEE 118-Bus Grid*

The method was further tested using 500 SUC on a modified IEEE 118-Bus grid. In 291 cases the topology was adapted. In 266 (91.1%) cases, the applied topological RA cause a reduction of the redispatch demand. In the remaining 25 (6.2%) cases, the demand increases. A maximum redispatch demand of 1782 MW occurred in the SUCs considered. The distribution of the achieved redispatch changes is shown in the histogram in figure 9.

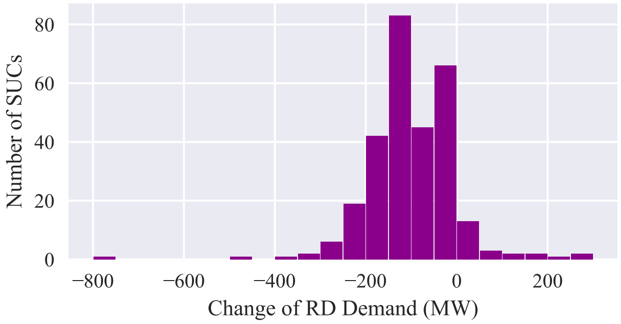

Figure 9. IEEE 118: Change of the redispatch demand

One possible reason for the larger number of SUCs with increasing redispatch demand compared to the IEEE 39-Bus grid is the grid topology and distribution of load and generation in the grid. The investigated 118-Bus grid has a less meshed structure in some areas. Furthermore, there are areas which mainly contain loads and no generators. In addition, the available redispatch potentials are somewhat lower. Consequently, the selection of the redispatch is more complicated. The previously explained problem of missing information on available redispatch in the context of topology optimization is thus aggravated.

These investigations show that the results of the presented method are generally good, but they also highlight the need for further development. Furthermore, the differences between the various grid models show that it is important to test the performance of the method on realistic grid models in order to identify specific needs for further development and to enable the best possible parameterization of the method.

## PEGASE 1354 Grid Model

In order to test the suitability of the approach for real grids, investigations were carried out using a modified version of the PEGASE 1354 grid model. The initial grid model originates from the Pan European Grid Advanced Simulation and State Estimation (PEGASE) project and represents the size and complexity of part of the European transmission grid [23]. Modifications were made for the investigations. The aim of the modifications was to create a suitable test case for the optimization of topology and redispatch. In order to determine the effects of the topology optimization on the redispatch demand, the initial topology of the grid and the load and generation situation were adapted in such a way that a congestion-free state can be achieved by means of redispatch.

Calculations have been performed on a single SUC varying the topological RA limit to investigate the influence of the number of selected topological RA on the redispatch required and the computation time. A set of 71 topological RA were considered as topological degrees of freedom. The effects on the redispatch demand are shown in figure 10.

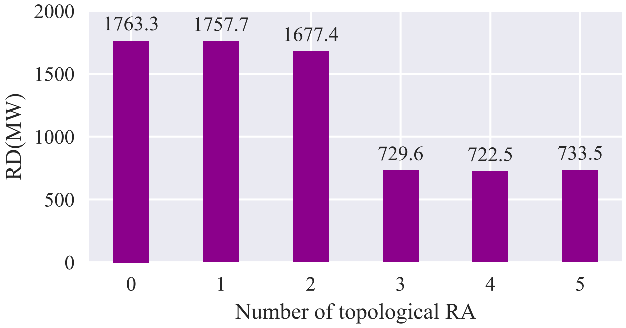

Figure 10. PEGASE-1354 redispatch demand

The results show that, as in the smaller grid models, it is possible to reduce the redispatch demand through topological actions. A strong reduction in the redispatch demand can be clearly seen when the topological remedial action limit is increased to 3. As explained above, one possible reason for this is the decoupling of topology and redispatch optimization. The topological actions that reduce the bottleneck power the most do not necessarily cause a strong reduction in the redispatch volume. Consequently, it is possible that actions with a major impact on the redispatch demand are only selected as a secondary option. It is also possible that combinations of actions may result that are more effective. Finally, approximation errors also influence the result, so that the effect of the action cannot be determined exactly. Therefore, additional actions can also lead to a renewed increase in the redispatch demand, as can be seen for action limit 5.

**Computation Time**

The presented optimization approach has been implemented in C++17 [26] and uses Gurobi solver version 10.0.1 [27]. All calculations were performed on a test system with 16 GB of RAM, equipped with an i7-1051U, clocked at 1.8GHz. Multi-threading was disabled in all computations. The test scenarios and resulting computation times are shown in table 3. Computation time includes the load flow, sensitivity calculation and optimization times.

TABLE III. COMPUTATION TIMES

| Model | Branches | Topology RA | Topology RA limit | Computation Time |
|---|---|---|---|---|
| IEEE-39 | 87 | 14 | 3 | 5 s |
| IEEE-118 | 361 | 33 | 3 | 1 min |
| PEGASE-1354 | 1920 | 71 | 1 - 5 | < 2min |

The stated computation times give a first impression of the order of magnitude of the computation times depending on the grid size and the topological degrees of freedom considered. However, there are other influencing variables such as the available redispatch and the initial grid situation. More extensive investigations are required for a more precise evaluation of the computation times.

Based on the results, acceptable computation times of the presented method should be achievable with a restriction of the solution space by preselecting suitable switching actions. However, 24 hours of the following day usually have to be optimized in a time-coupled manner for use in the TSO's operational planning processes. Higher computation times are therefore to be expected when using the method presented. Parallelization options, e.g. for power flow and sensitivity calculations, can be helpful in reducing the computation time. In addition, further options for reducing the complexity of the problem should be investigated.

## VI. CONCLUSION

Optimizing grid topology in conjunction with redispatch and PSTs can add value in ensuring grid security. The results show that the bottleneck power and the necessary redispatch can be reduced by topological RA with the presented method. Furthermore, acceptable computation times were achieved when the solution space is restricted. However, extensions to the method are necessary in the future. The method must be extended to deal with the described problems arising from the decoupling of topology optimization and redispatch optimization. In addition, possibilities for taking into account reciprocal effects between switching actions have to be investigated. Furthermore, time-decoupled optimization is often required in operational planning and should therefore be integrated into the method. As these extensions further increase the complexity, further studies on computation time must be carried out. To ensure practical suitability, investigations must be conducted on realistic grid models for a wide range of SUCs.

With regard to computation times, it should be noted that promising approaches based on machine learning are at the center of recent research and enable very short computation times as time-intensive calculations are shifted to training. One example of this is the publication by Dorfer et al. (2022) [15], in which a RL-based method for optimizing topology and redispatch was presented. However, there is still a need for further research into these methods, e.g. to enable the coordination of topological actions and redispatch and to ensure the suitability for grid operation. In the future, it will be useful to compare various suitable approaches to topology and redispatch optimization to determine the advantages and disadvantages of the methods. Due to the iterative process approach, the presented method also offers a starting point for hybrid approaches based on machine learning and mathematical optimization. In this way, the advantages of the different approaches could possibly be better utilized.

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