

FEEDBACK-DRIVEN TOPOLOGY OPTIMIZATION IN TRANSMISSION GRIDS

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Abstract: Topology optimization offers cost saving in congestion management but requires complex formulations and consideration of many additional constraints. Feedback-driven topology optimization could reduce effort by using expert knowledge to guide optimization in a desirable direction. This paper develops requirements for topology optimization human machine interaction (HMI) interfaces and presents a prototype graphical user interface (GUI). Based on real-world constraints, two requirements are derived: topological editing and reoptimization. A prototype GUI is presented, which enables operators to iteratively guide the reoptimization process. Using the GUI, a case study was conducted, which achieved a large reduction in switching effort in exchange for minimally higher costs. Feedback-driven reoptimization cycles enable operators to efficiently consider real-world constraints and make trade-off decisions informed with data.

Keywords: topology optimization, optimal transmission switching, optimal busbar splitting, congestion management, human machine interaction, topological actions.

1 Introduction

Driven by Germany's energy transition, grid congestions arise more frequently and in growing severity [1]. Transmission system operators (TSOs) are responsible for operating the transmission grid and are tasked with ensuring safe and stable operation [2]. For congestion management TSOs have multiple options, ranging from cost-efficient grid related remedial actions (RA) such as topological actions, phase-shifting-transformer (PST) tap changes or high-voltage-direct-current (HVDC) setpoint adjustments to more costly market related RA such as redispatch or countertrading. Remedial action optimization (RAO) describes an optimization software which TSOs use to determine necessary and economically efficient RA deployment [3]. RAO software used in Germany is based on (mixed-integer) linear programming (MILP), allows for formulating constraints within a mathematical model and optimizes market-related RA deployment as well as HVDC setpoints and PST tap positions for cost-efficient congestion management [4]. Topology optimization refers to RAO which additionally optimizes topological actions using existing grid infrastructure such as switching equipment to influence grid impedances and therefore alter the resulting power flow and/or congestion situation. Topology optimization does not allow for efficient linearization and has highly discrete, nonlinear effects on the congestion situation. Moreover, the effect of other available RA on remaining congestions closely interdepends on the grid impedances, which are altered by topological actions. Additionally, topological actions interfere with constraints such as voltage angle and magnitude difference limits between decoupled busbars, short-circuit current limits and grid restoration procedures, which are mainly adhered to by maintaining a well-known and historically proven default topology. Deviating from this topology

mandates validation of all relevant constraints. [5]

Due to the aforementioned complexity of integrating topology optimization into existing RAO, in Germany, topological actions are mostly optimized based on expert knowledge, as topology optimization software is not yet able to reliably include all relevant constraints in the optimization.

In this work we explore the applicability of human machine interaction (HMI) within an existing topology optimization method, enabling a feedback-driven optimization scheme. This approach includes reviewing proposed topological actions and editing or adding solutions based on expert knowledge as well as quickly reoptimizing reusing problem information from prior optimizations. This approach is visualized in Figure 1.

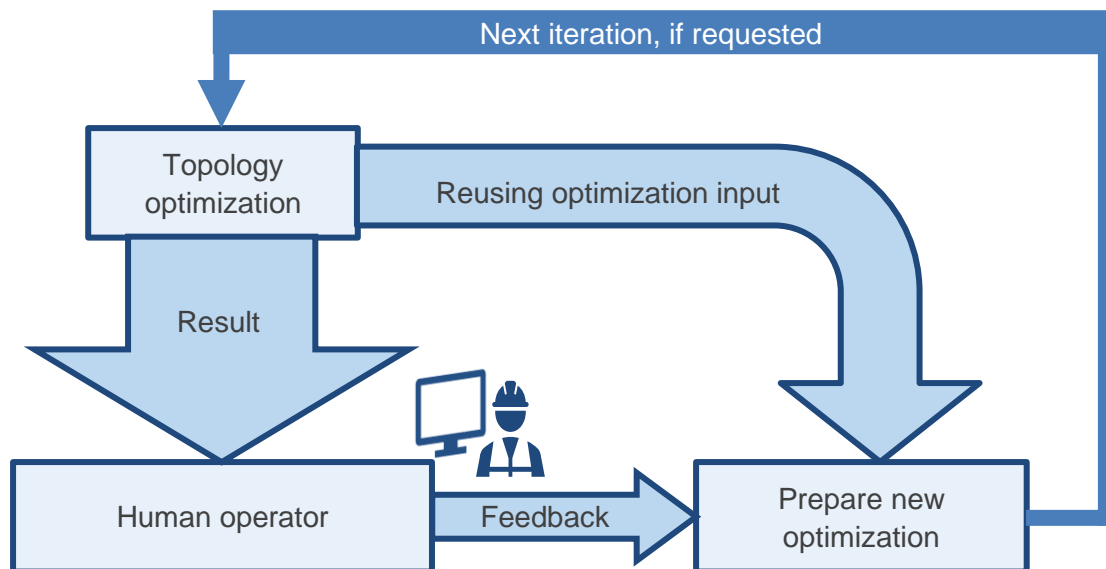


Figure 1: Human machine interaction schematic. The process may iterate until all operator feedback is adequately considered.

Our main research questions are:

1. What requirements for the use case “topology optimization” do HMI systems need to fulfill?
2. How can operator feedback be integrated into an existing methodology for topology optimization based on robust topologies?

Consequently, our work first discusses different requirements that HMI in topology optimization must fulfill. Afterwards we present an HMI prototype fulfilling a subset of the previously identified requirements as well as a short case study applying the HMI prototype to a test data set.

2 Analysis of Requirements for Human Machine Interaction in Topology Optimization

This section divides requirements into two key areas, *reviewing* and *editing* of topological actions, and presents an area of secondary importance, *reoptimizing* while considering operator feedback.

2.1 Reviewing Proposed Topological Actions

Topological actions may only be implemented in reality if they adhere to numerous constraints. The following Table 1 denotes the constraints that must be considered when implementing topological actions [4]. The rightmost column denotes whether mathematical formulation within a MILP is directly available. We refer to a “non-direct consideration” if e.g., constraints are either soft constraints, complex “if-this-then-that”-rules, can only be indirectly modeled or if necessary data is not readily available within congestion management.

| Class | Constraint description | Direct consideration in topology optimization available |
|-------------------------|---|---|
| Technical constraints | Current/Voltage Limits (initial & in contingency situations) | Yes |
| | Current/Voltage limits at neighboring and underlying grid operators | Yes |
| | Short-circuit current limits | No |
| | Grid connectedness | Yes |
| | System stability considerations | No |
| Operational constraints | Scheduled equipment unavailability | Yes |
| | Equipment wear minimization | No |
| | Validation effort for validating topological actions | No |
| | Implementation effort for topological actions | No |
| | Compatibility with upcoming planned topological actions | No |
| | Operator or maintenance personnel availability | No |
| | Switching sequence (transition sequence) | No |
| | Grid restoration process requirements | No |
| | Switch service life requirements | No |

Table 1 Overview over relevant constraints for topological actions within topology optimization [4]

An HMI interface ideally provides visualizations and analysis tools for each of the constraints from Table 1 where straightforward algorithmic implementation or validation is not possible or optimization time would rise significantly. Looking at Table 1, we observe that this mostly concerns those constraints which we refer to as *operational constraints*. Operational constraints are all constraints which are not a direct consequence from electrophysical equipment or protection system limitations. Instead, they comprise constraints that ensure a sustainable deployment of topological actions, considering soft factors such as personnel availability or ease of topological action implementation. Generally, they regard preferences of the operators and thus ensure acceptance of topological actions as RA. Weighing opposing goals, such as reducing staff utilization and validation effort for implementation while maximizing congestion remediation yield from topological actions needs operators to decide on efficient solutions including all constraints that cannot trivially be included in RAO.

HMI interfaces are able to leverage expert knowledge and situational awareness of operator personnel to incorporate consideration of these remaining constraints in topology optimization methods. HMI interfaces should therefore ideally include a graphical user interface (GUI) for reviewing each topological action as well as its local effect on currents and voltages. For displaying topological actions, each action should be displayed in the context of its individual substation layout, showing substation layout, switch states and power flow results. Ideally, a GUI is able to highlight differences in switch states or large resulting deviations in equipment utilization or voltages. Optionally, to enable analysis of regional effects of topological actions, a GUI should be able to display adjacent substations and their changed power flow results caused by the topological action.

As topological actions interdepend on other deployed RA, three different power flow simulation results are identified as relevant:

1. Power flow situation before topological action or other RA (severest N-1 and N-0)
2. Power flow situation after topological actions (severest N-1 and N-0)
3. Power flow situation after topological actions and other RA (severest N-1 and N-0)

Operators may be interested in analyzing each situation under normal conditions or during the severest contingency situation, but with different RA combinations. Especially, being able to analyze the isolated effect of proposed topological actions allows to assess the efficiency of each action without additional effects by other RA.

2.2 Editing Topological Actions

After review, operators are ideally able to

1. confirm and fix a topological action,
2. edit, add or forbid a topological action.

The GUI will treat these actions as shrinking or enlarging the solution space in the underlying topology optimization model. If a topological action is confirmed and fixed, the solution space will be reduced and does not further include this topological action as degree of freedom. Editing a topological action may also include fixing a topological action. Hence, editing either shrinks and/or changes the solution space. Forbidding a topological action results in a smaller solution space as well. Subsequent optimizations may profit from the reduced solution space by having shorter optimization runtime.

How a GUI is able to offer topological action editing depends on the GUI system, but interactively editing the substation layout identified in section 2.1 as a requirement remains a viable option.

2.3 Efficient Reoptimization

After reviewing proposed topological actions, the operator may request a new RAO to consider the topological editing. Moreover, this new RAO may be conducted only for the edited subset of timesteps, thereby decreasing subsequent RAO runtime. This is achieved by setting different reoptimization modes for each of the optimized timesteps. For timesteps with fixed topological actions, topology is no longer a degree of freedom. For edited topological actions the new RAO should allow for defining the topological solution space in higher granularity.

Operators should be able to easily include or disallow topological actions in the subsequent RAO. Not only does this reduce RAO runtimes but also prevents the optimization from deviating too much from the known solution. Reoptimization therefore includes the following three modes for each timestep:

- *Static*: Topological actions are considered fixed
- *Selective*: Available topological action solution space is subset of initial solution space
- *Full*: Complete topological action solution space is available

Changing between these modes enables operators to easily apply, fix or reoptimize topological decisions in each timestep separately.

3 Graphical User Interface (GUI) design

In this work we developed a prototype for an existing topology optimization method [4][6]. Section 3.1 gives a short overview for the existing topology optimization method.

3.1 Topology optimization result

Available academic and industrial topology optimization methods mainly differ in how the large combinatorial complexity of topological actions is restricted. For GUI design, two approaches are important to distinguish: Optimization methods where each switch is a degree of freedom and methods where well-combined switch states are set into full topologies that are invoked as one. Latter methods are only able to choose full topologies instead of individual switch states. Switch-related degrees of freedom are hence limited and instead modeled as topological degrees of freedom.

In this work, the developed GUI prototype is applicable to a topology optimization model presented in [4]. This method preselects suitable topologies and in a joint Co-Optimization of topology and other RA, a single topology (possibly comprising of multiple topological actions) is selected per timestep. This ensures a tradeoff between complexity and joint topology/RA optimum.

3.2 GUI Prototype: Tabs and Functions

The GUI starts once the initial RAO returns results. The GUI does not fully adhere to the requirements laid out in Section 2. It consists of multiple tabs, which are ordered in the proposed validation workflow-order:

- Tab “Results” with an overview over resulting topologies from the newest optimization
- Tab “Selection”, where topologies for reoptimization are selected and the solution space is reduced/expanded
- Tab “Review Topology”, where single topologies and included topological actions may be reviewed
- Tab “Review Topological Action”, where a topological action may be reviewed/edited
- Tab “Results Table”, where additional information for the newest optimization is shown
- Tab “Review All Topologies”, where all topological actions across topologies are shown to identify topological similarities across timesteps

3.2.1 Tabs “Results” and “Selection”

The tab “Results” initially displays the chosen topologies for the optimized timesteps in a matrix where each chosen topology is indicated. The next tab “Selection” is built similar but also allows for enlarging and shrinking the topological solution space, up to the fixation of topologies for desired timesteps (see Figure 2).

Internally, the GUI tracks the number of topologies with checkmark per timestep and will set the reoptimization mode to either *static*, *selective* or *full*, depending on the checkmarks’ states. A shortcut is the “Determine optimal Topology” row which will be interpreted as setting mode to *full* for the chosen timestep. The distinction in presenting the result and altering the solution space is intentionally, as comparing the changes to the original result is only possible if both initial result and applied changes are clearly distinguishable.

This tab also allows starting a new RAO after review and editing. A button allows for sending the configuration to a new optimization. Internally, most of the previously used RAO input data may be reused. Most importantly, runtime intensive sensitivities are only computed for edited topologies which achieves a large runtime improvement when having multiple review-, edit- and reoptimization-cycles.

| Fixed Topologies | | | | | |
|--|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Double click to view & edit topologies | | | | | |
| | Hour 1 | Hour 2 | Hour 3 | Hour 4 | Hour 5 |
| Base Topology | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 1 | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 2 | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 3 | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 4 | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 5 | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 6 | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 7 | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 8 | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Topology 9 | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |
| Determine optimal Topology | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

Figure 2 GUI Tab “Selection” - In this example, the base topology and topologies 1-3 are eligible to be chosen in the first timestep. In timestep 3, the optimal topology will be chosen from all possible topologies. In the other timesteps, the topological degrees of freedom have been fully fixed.

3.2.2 Tab “Review Topology”

The next tab opens, once the operator clicks on a topology in a specific timestep or on the row name for editing the topology for all timesteps. Here, all individual topological actions contained within this topology are visible and presented in their substation layout. Power flow simulation results are visible within the layout and depict all relevant equipment utilizations as well as voltage magnitudes and angles. Directions of active power flow are indicated for each feeder by a small arrow. Additionally, non-connected busbars are clearly distinguishable by differently colored feeders.

Our prototype is not yet able to display power flow simulation results for the most severe contingency situations or other metrics such as short-circuit current levels. Additionally, RA deployment data, such as deviations in power infeed for each generator, are missing from the substation layout. Instead, these results are displayed as a table in the following GUI tab.

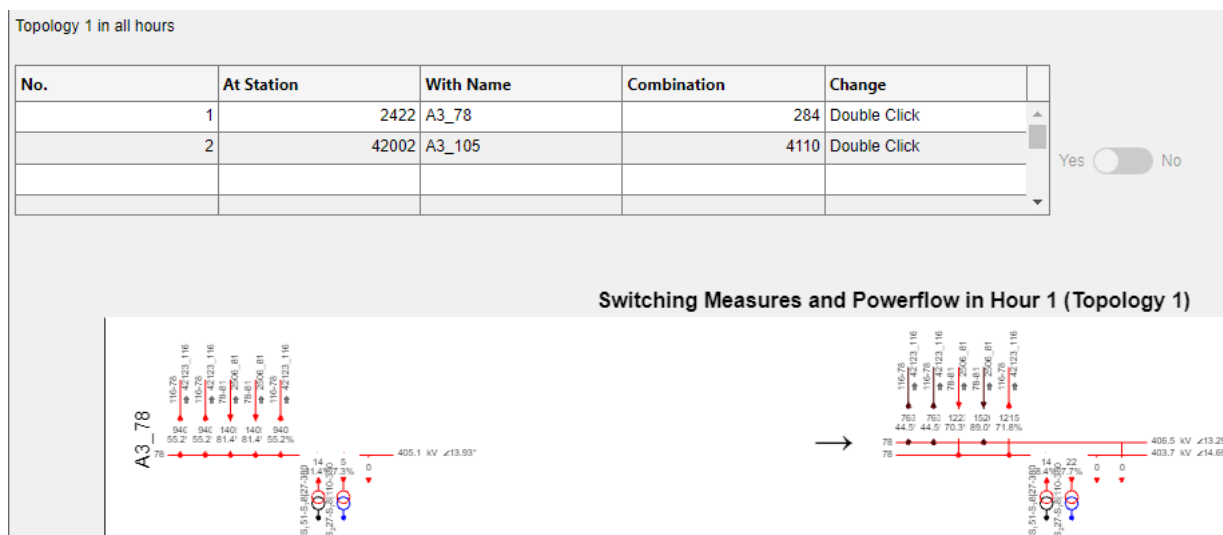


Figure 3 GUI Tab: “Review Topology” - Topological actions are shown at the top, while the topological actions are shown in their substation layout before (left) and after (right) implementation of the topological action.

3.2.3 Tab “Results Table”

This tab gives a tabular overview on the newest RAO result. It gives an example on how the RAO result might be displayed. To better comply with the requirements laid out in Section 2, a more comprehensive look into prior RAO result, possibly including links between topological actions and nearby changes to RA in each timestep, could be added to the summarized overview shown in Figure 4.

| Hour | Topology | Clock_Time | cb_abs | off_abs | on_abs | pp_abs | pp_pos |
|------|----------|------------|--------|---------|------------|------------|--------|
| 1 | 4 | 0 | 0 | 0 | 939.2078 | 1.1674e+03 | 1.0533 |
| 2 | 4 | 1 | 0 | 0 | 1.0873e+03 | 1.3219e+03 | 1.2046 |
| 3 | 4 | 2 | 0 | 0 | 614.7479 | 826.5359 | 720. |
| 4 | 4 | 3 | 0 | 0 | 1.3965e+03 | 1.6636e+03 | 1.5301 |
| 5 | 4 | 4 | 0 | 0 | 2.4700e+03 | 2.6561e+03 | 2.5631 |
| 6 | 3 | 5 | 0 | 0 | 792.3650 | 946.9050 | 869. |

Figure 4 GUI Tab “Result table” - Currently a summarized overview for each of the currently optimized timesteps is shown. The columns denote the RA deployment by technology type. (cb: crossborder-Redispatch, off: wind offshore, on: wind onshore, pp: conventional power plants)

3.2.4 Tab “Review Topological Action”

Lastly, after reviewing the topological actions in a topology, an operator may change or add a topological action by choosing a topological action from the table in tab “Review Topology” (see Figure 3). This opens a tab where this topological action is displayed with more context. More context may refer to more in-depth analyses or a graphical representation of the topological action along its neighboring substations (possibly even including a regional area) to further review regional effects. In our prototype, a large representation of the substation layout is presented.

As this GUI tab’s main focus is editing topological actions, operators may change the busbar assignment of each connected equipment by clicking on the equipment. Removing this topological action entirely or adding topological actions at neighboring stations is also possible

via GUI elements. Topological action candidates from other available topologies, which are known for neighboring stations, are also available for selection.

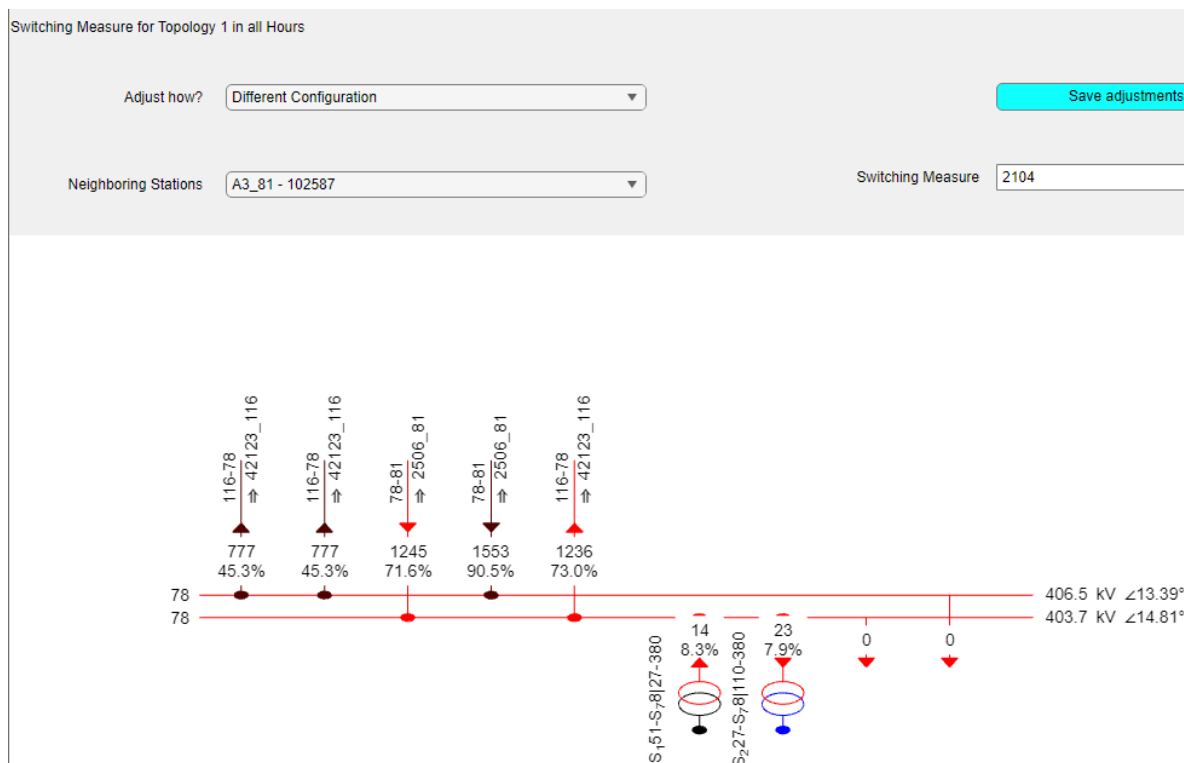


Figure 5 GUI Tab “Review Topological Action” - Here operators can manually switch busbar assignments through clicking on the desired equipment feeder.

3.2.5 Tab “Review All Topologies”

In this tab, the topological actions of all topologies are displayed in tabular form, enabling operators to quickly identify similarities across multiple topologies. For the ease thereof, station and branch names are fully shown, whilst specific station actions are abbreviated with letters.

| Topology | Measure_1 | Measure_2 | Meas |
|----------|-----------------------|------------------------|--------|
| 2 | St: A3_78, Measure: A | St: A3_105, Measure: A | |
| 3 | St: A3_78, Measure: B | St: A3_105, Measure: B | Line: |
| 4 | St: A3_70, Measure: A | St: A3_78, Measure: B | St: A3 |
| 5 | St: A3_78, Measure: B | St: A3_105, Measure: D | Line: |
| 6 | St: A3_78, Measure: B | St: A3_105, Measure: E | Line: |
| 7 | St: A3_78, Measure: B | St: A3_105, Measure: A | |

Figure 6 GUI Tab “Review All Topologies” - Contains a table with the different topological actions contained within every topology and enables cross-topological comparisons.

4 Exemplary Case Study

In the following section, an exemplary case study will be presented in order to demonstrate a possible use case of the developed prototype and of feedback-driven reoptimizations more broadly. This case study was conducted on a 120-bus benchmark grid (based on the IEEE

118-bus grid), which is modeled on the German transmission grid as expected in the year 2037 and is presented in [7]. Augmentation includes 2-busbar substation layouts at all substations at extra high voltage level. The initial RAO without topological changes, the generation of suitable topologies, and the second RAO with topological degrees of freedoms were calculated for a year, according to [4]. In order to accommodate certain prioritizations, renewable energy curtailment as RA is penalized in the objective function of the RAO higher than the actual cost thereof [4][8].

The case study investigates a 12-hour window in late December from 00:00 to 12:00. In RAO including topological actions an objective value reduction of 47.3% was achieved, whilst also reducing the renewable curtailment, showing the potential of topological actions in this time window.

As shown in Table 2 in the two left most columns, four different topologies were used. In the first five hours, all four of these topologies are selected; whereas in the final seven hours, all but one hour see a change to the selected topology, limited, however, to only two topologies. The number of topological actions solely within the time window, that is excluding actions at both beginning and end, total 76; it is not expected that this RAO solution would be acceptable to TSOs operators due to the large switching and validation effort (SE).

This use case presents a reduction in SE through an exemplary operator-guided iterative process. The complete topology review and editing process was conducted using the previously presented GUI prototype.

| Time-step | Topology | Substation reconfiguration | | | | | | | | | | | Branch switching | | | |
|----------------|----------|----------------------------|---|---|---|---|---|---|---|---|---|---|------------------|----------|---------|----------|
| | | Action | A | B | C | D | E | F | G | H | I | J | K | α | β | γ |
| 1 | 28 | | | | | | | | | | | | | | | |
| 2 | 48 | | X | | | | | | | | | | | | | |
| 3 | 48 | | X | | | | | | | | | | | | | |
| 4 | 46 | | | | | | | | | | | | | | | |
| 5 | 35 | | | | | | | | | | | | | | | |
| 6 | 28 | | | | | | | | | | | | | | | |
| 7 | 46 | | | | | | | | | | | | | | | |
| 8 | 28 | | | | | | | | | | | | | | | |
| 9 | 28 | | | | | | | | | | | | | | | |
| 10 | 46 | | | | | | | | | | | | | | | |
| 11 | 28 | | | | | | | | | | | | | | | |
| 12 | 46 | | | | | | | | | | | | | | | |
| No. of changes | | 0 | 2 | 2 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 2 | 7 | 7 | 7 | |

Table 2 Total switching effort for the first RAO with topological degrees of freedom. Where not color contrasted, topological actions at given stations are the same across all topologies. At station B, only topology 48 (in timesteps 2 and 3) has a different topological action.

4.1 Switching and Validation Effort Reduction through Iterative Process and Topology Alteration

As is shown in Table 2, the selected topology alternates between 28 and 46 from timestep 6. It is hypothesized, that there are neither large alternating changes in the generation pattern nor in the resulting power flow; hence, the impact of both topologies is likely similar, which is further supported by the three shared topological actions A, B, and C.

In order to test this and to see how SE reduction could optimally be achieved, two topologically static RAO were run through the GUI. Topologies before timestep 6 were left as selected by the second RAO. In the first topologically static RAO, topology 28 was used from timestep 6, in the second, topology 46. The maximum objective function increase in either RAO was 0.5 %, confirming the proposed similarity of the topologies. Furthermore, topology 46 was shown to be slightly better than topology 28. For the final RAO, topology 46 was statically fixed for timesteps 6 – 12 in the GUI tab “Selection”.

Building thereupon, the topology 35 in timestep 5 was replaced by its temporal neighbor, topology 46. Additionally, topology 48 was also fixed for timestep 1. To further reduce SE, topology 48 was adjusted by substituting the topological action at station B by the topological action at that station found in the other topologies, resulting in a new topology called 48' (see Table 3). In aggregate these actions reduce the number of topological actions to 10, an 86.8 % reduction compared with the initial topology optimization.

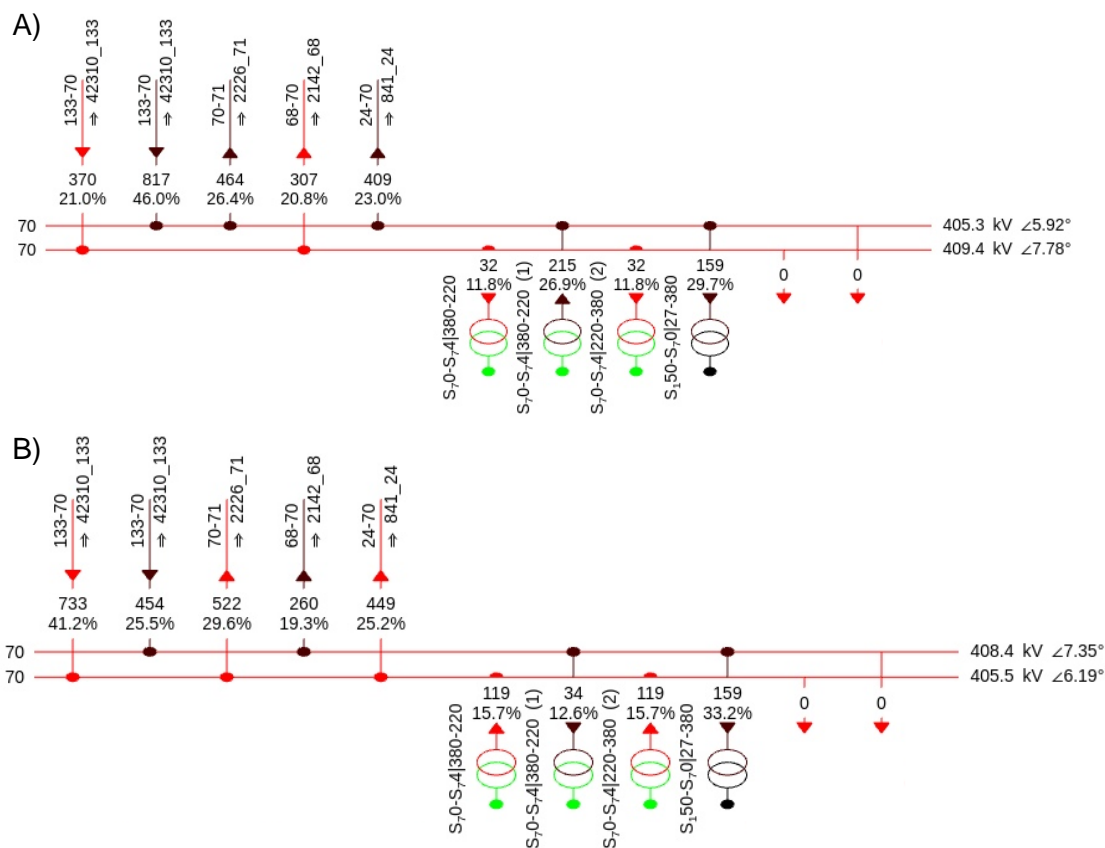


Figure 7 Excerpts from the GUI tab “Review Topological Action” - In Subfigure A) the station B with the original topological action is shown. Subfigure B) shows the station layout of the other topologies, including 48'. Red corresponds to the 380 kV level, green to the 220 kV level and black to the 110 kV level. The power flow is shown for the N-0 case.

Figure 7 shows the station configuration for topological action B in topology 48 and 48'. Switching between these topologies involves three busbar reassignments, increasing the SE. The GUI was used to check requirements laid out in Table 1, e.g. the power flow into the underlying 110 kV grid does not significantly change when using the topological action of topology 48'.

In the final, topologically static RAO, the objective value deteriorates by 0.2 % when compared to the topological optimization. It is to note, however, that the selected topological schedule was not contained in the original solution space and was only available by leveraging the proposed GUI functionalities and operator knowledge. Figure 8 shows the redispatch energy, resulting costs, and renewable curtailment for each timestep. In timesteps 2 and 3, whose topology was adjusted with a topological action substitution, a minimal increase in cost occurs. Whilst the original topology 48 was better fit for those hours, the tradeoff of a slight cost increase for reduced SE is acceptable.

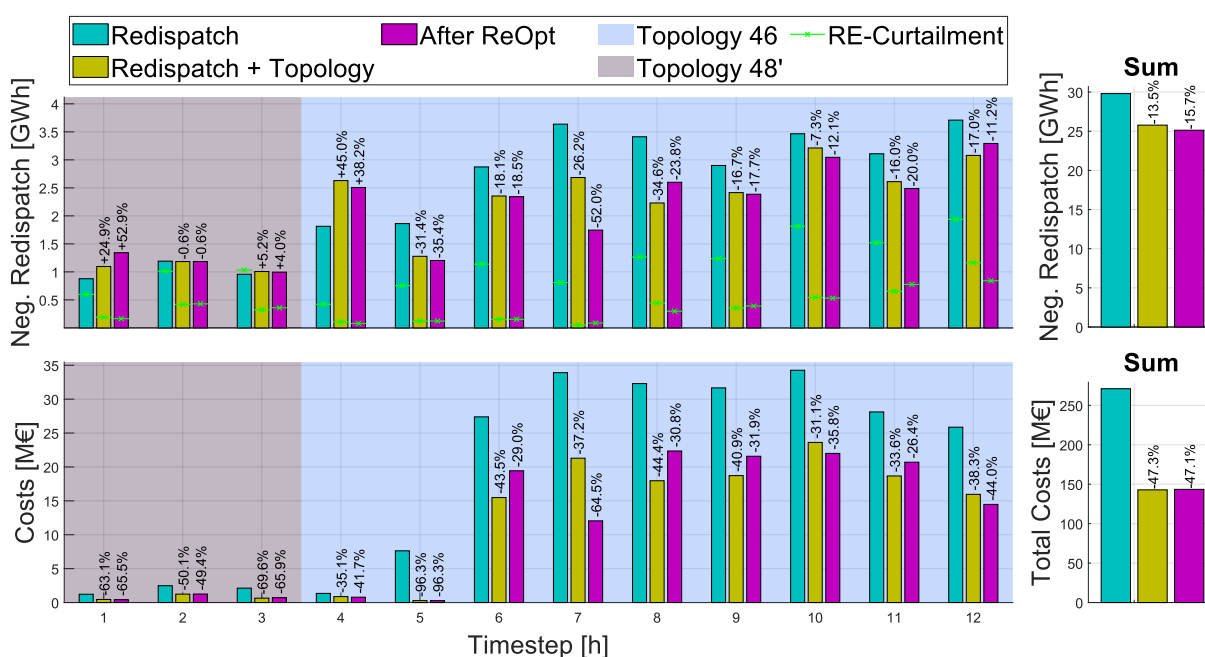


Figure 8 Redispatch energy and objective value for all timesteps initially before topology optimization and before and after operator feedback. Percentages are always in relation to the result of the RAO without topology as degree of freedom.

Timestep 7 showcases a large reduction in costs, despite no topological changes in the hour itself, showing the impact of time-coupling constraints such as ramping constraints of thermal power plants. While timestep changes to costs or redispatch energy can be discussed in the context of timestep topological alterations, this can neglect the possible time-window-wide effects of individual timestep-contained topological adjustments.

Table 3 shows the final topological action schedule after successful HMI.

Overall, the reoptimization process and the GUI enable here the tradeoff of significantly less SE and a minimally worse solution. Furthermore, requirements presented in Table 1 can be validated through the GUI and the power flow visualization of specific topological actions therein.

| Time-step Action | Topology | Substation reconfiguration | | | | | | | | | | | Branch switching | | | |
|---------------------|----------|----------------------------|---|---|---|---|---|---|---|---|---|---|------------------|---------|----------|--|
| | | A | B | C | D | E | F | G | H | I | J | K | α | β | γ | |
| 1 | 48' | | | | | | | | | | | | | | | |
| 2 | 48' | | | | | | | | | | | | | | | |
| 3 | 48' | | | | | | | | | | | | | | | |
| 4 | 46 | | | | | | | | | | | | | | | |
| 5 | 46 | | | | | | | | | | | | | | | |
| 6 | 46 | | | | | | | | | | | | | | | |
| 7 | 46 | | | | | | | | | | | | | | | |
| 8 | 46 | | | | | | | | | | | | | | | |
| 9 | 46 | | | | | | | | | | | | | | | |
| 10 | 46 | | | | | | | | | | | | | | | |
| 11 | 46 | | | | | | | | | | | | | | | |
| 12 | 46 | | | | | | | | | | | | | | | |
| No. of changes | | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | |

Table 3 Total switching and validation effort for the final RAO. All actions are the same across all topologies, where not color contrasted.

5 Conclusion and Outlook

This work demonstrates that computerized topology optimization in transmission grids benefits significantly from close, iterative interaction with human operators via dedicated human-machine interfaces (HMIs). By enabling operators to review, confirm, edit, add, or forbid topological actions and to control the reoptimization mode on a per-timestep basis (*static*, *selective*, *full*), the proposed graphical user interface (GUI) prototype directly embeds operational expertise into the optimization loop and addresses operational constraints that are difficult to model explicitly in remedial action optimization (RAO). In doing so, the proposed feedback-driven approach mitigates drawbacks of the underlying topology-based optimization method, especially its tendency to generate topology schedules with high switching and validation effort (SE), by allowing operator-guided review and editing of the topological solution. Because intermediate RAO data such as power flows are reused and recomputed only for edited topologies, repeated review-, edit- and reoptimization-cycles become computationally feasible, supporting frequent validation and refinement of topology optimization results in practical congestion management workflows. The exemplary case study confirms that such an interactive and iterative HMI process can drastically reduce switching effort (by about 86.8 %) at the cost of only a very small deterioration in the objective value (around 0.2 %), thereby achieving a more operationally acceptable compromise than the purely algorithmic robust-topology solution.

Future development will focus on closer integration of multi-timestep substation layout views to allow for an easy cross-timestep inspection of the intermediate results. Also, analyses and resulting statistics on the switching and validation effort are to be integrated into the review tabs of the GUI to enable prompt identification of operationally challenging topology schedules.

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