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Summary

Congestion is one of the major system risks for transmission system operators. At the same time, topological remedial actions still represent a largely unexploited form of non-costly flexibility due to the combinatorial explosion in the number of possible actions. The GridOptions Tool recommends to operators topological remedial actions to mitigate congestion in the day-ahead/intraday timeframe. The underlying optimization approach is based on two pillars: (i) very fast load flow computations enable screening of the full set of relevant topologies, and (ii) multi-objective quality-diversity optimization enables the generation of a set of strategies which satisfy different trade-offs between various objectives and are behaviourally diverse. The considered objectives are related to both physical security constraints and the complexity of the strategies. As a result, the tool generates topological strategies that are a significant improvement compared to both the situation in which no topological remedial actions are applied and the known operator strategies. Moreover, the GridOptions Tool offers a simple user interface which is developed in interaction with operators to satisfy their cognitive needs. Finally, the GridOptions Tool is largely based on open-source tooling, and all components can run as a Docker container on a Kubernetes platform.

KEYWORDS

Congestion Management, Topological Remedial Actions, Decision Support, Multi-Objective Quality-Diversity Optimization, Artificial Intelligence, DC Load Flow, Human-Machine Interface

1. Introduction

The electricity system is changing rapidly, due to the increasing efforts against climate change. Electrification of the industry, the built environment and the transportation sector significantly increases the demand for electricity. This demand will need to be generated by variable renewable energy sources such as solar and wind, which are less controllable, are geographically distributed and exhibit large variations in output. This increased weather dependency results in a transformation from a demand-driven towards a supply-driven electricity system. These developments require the electricity grid to significantly increase transport capacity in the future and already stretch the current grid to its limits. In the control room, operators are already being challenged by the changing system behaviour, and maintaining a high level of security of supply is expected to become even more challenging in the future [1].

To cope with these challenges, new tools and functionalities, such as forecasting and decision support tools are needed. Therefore, TenneT has launched the Control Room of the Future (CROF) program to support the development of tools when no commercial alternatives are available. As a starting point for the CROF R&D roadmap, system risks have been identified, with congestion being one of the main concerns, despite all current and future efforts on grid expansion. In the Netherlands, the increased congestion issues have already led to customers being denied new/larger connections in a growing number of regions. Secondly, maintenance regularly needs to be postponed because the grid cannot afford certain elements to be taken out of service. Additionally, congestions that still arise, despite constraining new customer connections and maintenance, have led to a significant increase of redispatch costs in the Netherlands over the last few years [2].

For these reasons, the GridOptions project has been started as one of the first projects under the CROF program. The goal of this project is to develop a tool that can provide decision support on topological measures to solve congestion in a more effective and efficient way. This will contribute to the following aspects:

- By increasingly exploring the topological solution space, the tool can find, assess, and propose new solutions that were formerly unexploited, hence contributing to the security of supply.
- By leveraging the (non-costly) topological remedial actions the costs for congestion management can be reduced.
- By finding more capacity in the transmission grid, especially the meshed parts of the grid, maintenance can be facilitated, and new customer connections or expansions can be enabled.
- By generating recommendations in a short amount of time, the response time can be decreased, which is getting increasingly important considering the increasing volatility in the grid.

In this paper we report on the first version of the GridOptions tool. The paper is structured as follows: In Sections 2 and 3 we describe more precisely the TenneT use case and the scope and requirements of real-world (day-ahead) congestion management. In the main section of this article, Section 4, we outline how the GridOptions tool addresses these requirements in terms of backend (i.e. employed algorithms), frontend (i.e. visualization), and architecture (i.e. data pipelines, tooling). Subsequently, in Section 5 we report on the application of the GridOptions tool at TenneT. The paper closes with a summary and future work directions (Section 6), e.g. for later versions of the GridOptions tool.

2. TenneT use case

Within the European market, a Transmission System Operator (TSO) is responsible for managing congestion on the transmission grid of 110 kV and above. TenneT as the Dutch TSO therefore performs a network security analysis within multiple timeframes, including the intraday timeframe. This process starts the evening before the business day and in this process, it is assessed whether the grid is expected to be safe in terms of currents, voltages and other criteria. For this process, power forecasts and the security limits of the grid elements are considered.

The TenneT use case is focussed on a part of the 110 kV grid in the Netherlands that has limited transport capacity. Moreover, this is an area where land is relatively cheap, leading to a sharp increase in requested customer connections for solar parks. Consequently, operators are confronted with new (more generation-dominated) flow patterns, so that they need to operate the grid with an increasing number of interventions and/or closer to its limits. The core question is: Are topological actions capable of mitigating (at least partly) overloads? Dynamic grid topology reconfiguration is an interesting option for system operators since it is a cost-efficient and flexible solution for congestion management that uses existing infrastructure. But it is still beyond the state-of-the-art to optimally control the grid topology "at scale" due to the problem's nonlinear and discrete combinatorial nature leading to a large search/optimization space. Moreover, the real-world problem is not a single snapshot problem but rather the optimal topologies must be determined considering the variation of load and generator injections over a time horizon (a day in the use case) and the ability to change between topologies.

3. Scope of real-world congestion management in GridOptions tool

Congestion management is a real-world decision problem that is characterized by large action spaces, sequentiality (including different time horizons), uncertainty, behavioural diversity, and multiple objectives. Due to the latter, decisions often need to be taken in the presence of trade-offs between conflicting objectives. For example, system operators simultaneously need consider security constraints, hard time constraints, and financial costs. For that reason, the GridOptions tool approaches congestion management explicitly as a multi-objective decision problem. More precisely, the GridOptions tool is designed as a decision support tool which offers operators a set of optimal strategies (or schedules) that exhibit different trade-offs between the different objectives. Here, a strategy is defined as a sequence of topologies, that is, a strategy specifies the network topology for each timestep of a day. The choice of the final strategy is left to the preferences of the human operator (possibly including information that was not available during computation).

Although congestion management of transmission grids has been studied in the research literature (see for example [3] and references therein), real-world decision support solutions need to satisfy specific requirements and constraints that are often (partly) neglected in initial proof-of-concepts and academic solutions. The scope of the first version of the GridOptions tool is summarized in Table 1. We note that next to the load flow-based objectives (i)-(ii) also objectives related to the topological complexity and the amount of switching actions are relevant. For example, objective (iii) implies that a baseline strategy (i.e. a topology that is used for the entire time horizon) is considered as a valuable strategy. We also would like to point out that the (scope of the) GridOptions tool is developed in close and regular interaction with human operators, because the trust of the user is crucial for real-world applications [4].

Specifications	(i) **Temporal scope**: Decision support is provided to the oper-ators in the grid security analysis that takes place in the evening before the business day using the injection forecasts for the next day. Consequently, the overall time horizon of the optimization is essentially one business day (ii) The geographical scope is kept small at the beginning to reduce the size of the action space. The focus is on a part of the Dutch 110kV grid that contains 9 controllable substations
Requirements	(i) Because operators perform the grid security analysis in the evening before the business day, it is acceptable to wait for about an hour to receive decision support. That is, the **inference/computation time** is one hour (ii) The decision support needs to be based on **real-world data**: operational TenneT grid models and the operational power forecasts will be used (iii) The **simulator used in operational** processes needs to be employed to produce the load flow results shown to the operators (iv) New strategies are benchmarked against strategies already provided/known by operators (**human operator strategies**) (v) **Busbar outages** should be included in the contingency analysis. In particular, not only busbar outages at higher voltage levels (usually without loss of injections) but also at lower voltage levels (leading to imbalance due to loss of injections) are relevant
Decision variables (remedial actions)	(i) Only **substation reconfigurations** are considered as remedial actions. For the TenneT use case there are 9 decision variables (i.e. substations) with each offering several configurations that can be chosen
Constraints	(i) Only topologies of maximal topology depth 3 are considered (i.e. maximally three busbar couplers are open) (ii) Only topologies with at least two branches connected to each busbar are considered.
Objectives	(i) Minimize the N-0 load flow (ii) Minimize the N-1 load flow (iii) Minimize the amount of switching timestamps (i.e. maximize the duration of active topologies) (iv) Minimize the number of open busbar couplers (i.e. minimize the topological depth) (v) Minimize the amount of switching when stepping from one topology to another (i.e. minimize the topological distance)

Behavioural descriptors	(i) Substations used for switching actions (ii) Exact timing of switching actions
User interface design	(i) Provide in tabular form a high-level comparison of the different strategies in terms of the different objectives (ii) Provide in tabular form detailed load flow results for each strategy, e.g. in a similar form as is used in the European intraday process (AMICA) (iii) For each strategy, indicate the topological changes for each substation with same graphical design as used in the EMS (iv) Indicate which elements cannot be switched remotely

Table 1 - Scope of the first version of the GridOptions tool in relation to 7 different scoping categories

4. Architecture and modules of GridOptions tool

In this section we first give an overview of the underlying architecture of the GridOptions tool. Subsequently, we describe the approaches employed in each module of the pipeline.

4.1. Underlying architecture

The GridOptions tool is based on open-source tooling, except for the commercial power system application (PowerFactory) that is also used in operational processes and therefore acts as the reference simulator. We build the application as cloud native, such that it can be managed and deployed by code. We package the application into Docker containers and deploy it in a Kubernetes cluster. By using Docker, we make the application portable and with a Kubernetes platform we lay the foundation of working in a cloud native environment. This ensures a standardized development and deployment process.

Figure 1 shows a high-level schematic of the architecture of the GridOptions tool. The process starts with Apache Nifi, which handles the ingestion of intraday grid models (including time series of injections) into HDFS. For each grid model a strategy generation module is run which comprises multiple Python applications (the modules are presented in the following subsections). Finally, the operational power system application is used to calculate the AC load flow related to each strategy.
Subsequently, Kafka is used to publish the results to multiple parties. The visualisation pre-processor listens to the result events, and then consumes and transforms the file-based output into a PostgreSQL database. By using database storage, the web application responsible for displaying the data will always show the most up to date data. On top of this we also export the data to HDFS which is provided by the TenneT Data Platform. This enables sharing the generated data with other initiatives within the TenneT analytics community.
The results are displayed to the end user – the operators – through a web application

built with Dash, chosen for its powerful data science visualisation tools. The web application retrieves the data directly from the database and does minor transformative work to show advanced metrics.

4.2. DC load flow: Fast brute-force computations

In the first step of our pipeline, we perform N-0 and N-1 load flow computations for all topologies and timesteps in scope. The fastest way to perform load flow computations is using the DC approximation combined with distribution factors which enable fast updates in case of line outages or bus splitting [5]. For this purpose, the grid model and time series of injections of a business day are extracted and made available in corresponding Python code.

In order to further reduce the computational efforts, we filter the topologies in scope by applying the following principles and *a priori* constraints to the topologies: First of all, in a DC setting it is natural to consider, on the one hand, how the branches of the network are connected to the nodes (i.e. busbars), and on the other hand, how the injections of the network are connected to the nodes. The branch configurations are crucial in specifying the network connectivity whereas the injections at a node can simply be aggregated into a single nodal power. Second, by considering only the branch configurations, the following filters can be applied to the topology space: (i) we filter out all topologies for which less than 2 branches are connected to a busbar in a controllable substation with open busbar coupler (see constraint (ii) in Table 1), (ii) we filter out all topologies for which any N-1 case leads to islanding (i.e. islands can be excluded before any load flow computation), and (iii) parallel branches that connect to dead ends (i.e. remote nodes that are not otherwise connected to the network) are combined and treated as one injection.

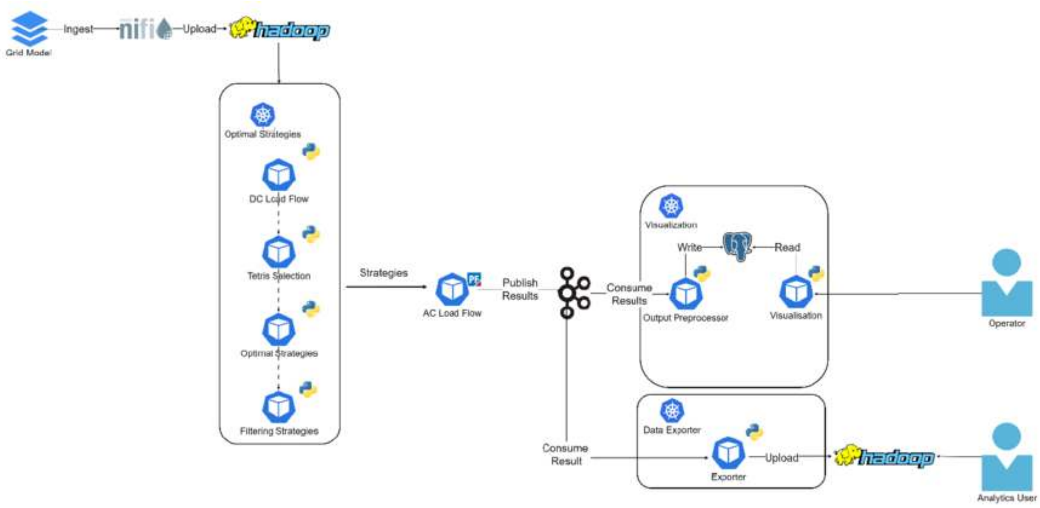

Figure 1 - Schematic of the architecture of the GridOptions tool

4.3. Filtering topologies: Tetris selection

The amount of load flow results created in module 4.2 is too large for directly optimizing strategies (see module 4.4). Hence, in module 4.3 a pre-filtering step is performed. For that we employ lexicographic ordering (LO) ([6], [7]) as simple multi-objective optimization. More precisely, our LO algorithm is named Tetris selection, and a pseudo-code is shown in Algorithm 1. It works as follows: For each timestep t, only topologies for which the load flow is within security limits are considered (applying objectives (i) and (ii)), leading to $n_{topo}(t)$ topologies per timestep. The availability $\alpha_\tau(t)$ of each topology τ per timestep t is given by the set of consecutive timesteps (including t) for which τ is available. For example, if a topology does not lead to overloads throughout the entire day, then its availability includes all timesteps of the day. The goal is to find at least nmin_topo topologies per timestep with long availability (objective (iii)). Hence, the result of the Tetris selection algorithm is a subset of topologies per timestep t, $\Theta(t)$, where each topology $\tau \in \Theta(t)$ has relatively large $|\alpha\tau(t)|$. In case of ties other objectives are used such as maximum load flow ratios (again objectives (i) or (ii)) or topological depth (objective (iv)). In loose analogy with the Tetris game, the key idea of this filtering step is to iteratively select topologies with long duration, so that at any timestep of the day a certain number of topologies is available. The topology with the longest availability (across all time steps) is selected first. Then, the process is repeated, but focusing on the topologies that are valid for the timestep that is covered by the least number of selected topologies. The outcome of this algorithm is a reduced (but still large) set of topologies (and related load-flow results). By design, the selected topologies are the most stable topologies available, and therefore most suitable for network operation.

while not $|\theta(t)| \in \{n_{min\_topo}, n_{topo}(t)\}\ \forall t$ **do**
    $\mathbf{t^* = argmin_t \{|\theta(t)|\ with\ |\theta(t)| \notin \{n_{min\_topo}, n_{topo}(t)\}\}}$
    $\mathbf{\tau^* = argmax_\tau \{|\alpha_\tau(t^*)|\ with\ \tau \notin \theta(t^*)\}}$
    for $\mathbf{t \in \alpha_{\tau^*}(t^*)}$ **do**
        $\theta(t).\mathrm{append}(\tau^*)$
    end for
end while
return unique $(\mathrm{concatenate}_t[\theta(t)])$

Algorithm 1 - Details, including definitions of the symbols, are given in the text of Sec. 4.3.

4.4. Optimal strategies: Random Sampling and shortest paths

To find optimal strategies, we employ random sampling (RS) [8] as a simple approach to multi-objective optimization. RS samples many sets of weights and creates a single-objective problem according to each sample of weights. The advantages of RS are that it immediately creates results, and it is easy to implement. The disadvantage is that RS is only optimal in the limit of a large number of samples. Usage of more sophisticated techniques is planned.

Subsequently, we solve the single-objective problem via shortest-path computation. More precisely, we build a decision graph, with each node being the state of the network (defined by a network topology at a given timestep, associated with load flow results) and each edge having a cost. The cost is a weighted sum of different operational costs associated with the transition from one state to another. The operational costs are defined by the objectives (i)-(v) in Table 1 such as the number of topological actions to perform and the resulting load flow. For example, staying in the same topology does not induce any topological action cost, but if it leads to larger load flows it could be less costly to switch to a different topology. Once this decision graph is built, it is straightforward to compute the optimal sequence of states (i.e. a strategy) as the path with the smallest cumulative weight between the initial state and the final states of the network (using Dijkstra's algorithm, as cost are non-negative by design).

As indicated before, the overall cost function includes a weight for each operational objective. For example, setting the weight of the topological action cost to one and the other weights to zero will lead to the calculation of the path minimizing topological actions but not necessarily the lowest load flow ratio. To present different trade-offs of the conflicting objectives, several sets of weights are sampled (using a Dirichlet distribution) and for each set of weights, the k best strategies are computed. Finally, this set is complemented with baseline strategies, defined as strategies associated with each single network topology that is available throughout the day (i.e., which optimize at least objective (iii) in Table 1). This results in a set of viable strategies satisfying a range of operational objectives.

4.5. Selecting strategies while keeping quality and diversity

All strategies constructed in module 4.4 are optimal for certain trade-offs of the different conflicting objectives shown in Table 1. However, the number of strategies created in module 4.4 is too large for the AC solver to solve or for the operator to grasp. Hence, a selection of strategies is performed in several steps. Firstly, strategies are clustered based on their similarity. Each cluster encompasses all those strategies that switch between the same set of topologies (without considering for how long each topology is maintained and at what timestep the switching happens). Clusters are then grouped by the set of substations affected. Subsequently, within each group a few representatives are chosen. Within a group, for each of the objectives shown in Table 1, we select an optimal strategy (amongst all the strategies in all the clusters in said group) that maximizes that objective individually. For the same group, we also select the strategy that maximizes the average of the objectives shown in Table 1. Finally, still for each group of clusters, we also select the top n strategies that minimize objective (iii) from Table 1. With usually 4-5 groups to consider, this leads to a selection of about 20-30 strategies per business day. In other words, in this module a form of multi-objective quality-diversity optimization [9] is performed since not only the objectives but also the behavioural descriptors of Table 1 are considered.

4.6. AC load flow: Contingency analysis of proposed strategies

Finally, with the results of module 4.5 a small set of strategies is available that can be used in the contingency analysis performed with the commercial power system application. Once the AC load flows (N-0 and N-1) associated to the selected strategies are computed, they are uploaded to the database and displayed in a web dashboard for the operator to inspect (see module 4.7).

4.7. User interface: Interactive dashboard for the operator

The GridOptions tool user interface offers several views such that the operators can interactively explore different topological strategies and related load flow results. In particular, it realizes the user interface design features (i)-(iv) indicated in Table 1 which are requested by the operators. Figure 2 shows an example view of the GridOptions dashboard related to design feature (i), namely, a table that gives a high-level summary of each strategy. The rows alongside each strategy show for each timestep of the business day the maximum load flow ratio (respectively N-1 and N-0), the number of substations to be modified during that time step and the number of open busbars couplers. The colors yellow and red indicate that certain warning thresholds are exceeded.

Concretely, in Figure 2 two strategies are depicted. The default strategy is “all_busbar_closed”, in which all busbar couplers are closed throughout the day. If feasible, this strategy is preferred by the operators, but for this specific business day this strategy shows a significant number of hours overloaded for the *N-1* analysis. An alternative strategy shows a complete mitigation of overloads except for one timestep.

Once an operator has identified a promising strategy it can be further investigated. For example, for a certain hour the operator can view the detailed load flow results of all N-1 computations, as shown in Figure 3 (design feature (ii)). Moreover, the operator can inspect substation views which show the altered switch states for each substation (design feature (iii), not shown). Finally, several ordering and filtering options are available such that the operator can analyse various trade-offs of the different objectives.

Number to display
2
Pinned strategies
Select strategy to pin
Advanced filters

		Wednesday																							
Strategy name	Indicator	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
all_busbars_closed	N-1							84	106	111	108	111	105	99	103	104	104	105	126	98	103	110	103	103	94
	N-0								75	91	82	90	86	81	85	86	86	86	99	80	75	77	78		
	# substation to change																								
	# open busbar couplers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
baseline_0	N-1								89	96	96	96	91	88	92	93	90	93	106	88	86	91		82	
	N-0									79		77					75	75	84						
	# substation to change	2																							
	# open busbar couplers	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Figure 2 - Example view of the GridOptions dashboard providing a high-level comparison of different strategies

Affected branch	Contingency case	Wednesday																							
Affected branch	Contingency case	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Branch 0	Grid Element 0									111	108	111	105	99	103	104	104	105	124	98			95		
Branch 1	Grid Element 1									109	106	109	103	98	102	103	103	104		96					
Branch 2	Grid Element 2									103	100	102	96	90	95	96	97	97	116	90			87		
Branch 3	Grid Element 3									101	98	100	94	89	93	95	95	96		89					
Branch 4	Grid Element 4								91	97	98	101	103	98	95	94	92	90	109	82			82		
Branch 5	Grid Element 5								83	92	95	96	91	87	89	88	90	93	119	88	80				
Branch 6	Grid Element 6									89	89	95	98	95	94	92	87	86					80		
Branch 7	Grid Element 7								80	86	87	91	91	87	85	84	82	82							
Branch 8	Grid Element 8								81	85	85	89	92	88	85	83	81		94						
Branch 9	Grid Element 9									82	81	88	92	88	87	86	80								
Branch 10	Grid Element 10									81	83	84							101						

Figure 3 - Example view of the detailed tables for exploring the N-1 results of a strategy, sorted for the hour 8:00. A comparable table for exploring N-0 results exists

5. Application of GridOptions tool at TenneT

The application of the GridOptions tool at TenneT as a first minimal viable product is promising in several respects. First, the tool proposes topological strategies that are a significant improvement compared to the situation in which no topological remedial actions are applied. More precisely, often relatively simple topological strategies (i.e. with few switching timestamps and few switched substations, objectives (iii)-(v) in Table 1) can reduce the loading of congested lines by 10-20% (objectives (i)-(ii) in Table 1). Figure 2 shows an example case in which the congestion at several hours can be mitigated by only switching two substations in the morning. Also, when comparing the proposed strategies with the strategies that operators often consider (not shown) a significant improvement is exhibited. A more detailed analysis of the proposed topological strategies and the related mitigation of congestion for a large set of congested days will be the subject of a separate article.

Second, dynamically updating the topological strategies (say a new set of strategies for each business day) poses a challenge in two respects: On the one hand, the brute-force optimization outlined in this article (sections 4.2-4.6) requires a significant amount of computation time (mainly due to 4.2 and 4.6). This can lead to inacceptable waiting times for the user. On the other hand, a new set of diverse topological strategies every day can lead to cognitive overload by the operators since each unfamiliar strategy needs to be thoroughly understood before it can be applied in the real world. To solve both issues, in the first deployment of the GridOptions tool a shortlist of fixed topological strategies is used for each business day. More precisely, modules 4.6 and 4.7 are executed online for every new business day with a fixed set of topological strategies. In contrast, modules 4.2-4.5 are performed offline and enable an analysis of topological strategies for a large set of historical days. The static list of strategies is updated with a lower frequency (e.g. once per month) based on this analysis and after evaluating the new strategies with the operators.

Third, the overall design of the decision support tool (with optimization algorithms only being part of it) is crucial to gain the acceptance and trust of the users (i.e. operators). For that the operators were constantly included in the development cycles of the tool so that the dashboard views integrate smoothly in the ongoing operational processes and connect seamlessly to the cognitive patterns in the minds of the operators (i.e. low cognitive effort for the operators to grasp the results). We emphasize that it is not a given that operators who are used to decision support which is solely focussed on problem identification (i.e. whether congestion arises) will trust decision support which also offers solutions to problems (i.e. ways to mitigate congestion). To gain acceptance by the user the solutions need to be adequately communicated. The GridOptions tool offers decision support in a rigorously multi-objective framework which keeps the operators in the driver's seat and helps to gain their acceptance of the tool.

6. Summary and future work

Congestion is one of the major future system risks for transmission system operators. At the same time, topological remedial actions still represent a largely unexploited form of non-costly flexibility due to the combinatorial explosion in the number of possible actions. The GridOptions Tool recommends to operators topological remedial actions to mitigate congestion in the day-ahead/intraday timeframe. The underlying optimization approach is based on two pillars: (i) very fast load flow computations [5] enable screening of the full set of relevant topologies, and (ii) multi-objective quality-diversity optimization enables the generation of a set of strategies which satisfy different trade-offs between various objectives and are behaviourally divers. The considered objectives are related to both physical security constraints and the complexity of the strategies. As a result, the tool generates topological strategies that are a significant improvement compared to both the situation in which no topological remedial actions are applied and the known operator strategies. Moreover, the GridOptions Tool offers a simple user interface which is developed in interaction with operators to satisfy their cognitive needs. Finally, the GridOptions Tool is largely based on open-source tooling, and all components can run as a Docker container on a Kubernetes platform.

The GridOptions tool can be improved or extended in several ways. Table 2 gives an overview of possible future directions. Obvious next steps include increasing the geographical scope, including additional types of decision variables, and applying the tool in more operational timeframes (e.g. during outage planning as well as closer to real time). To enable these steps, it is crucial that the optimization algorithms can be accelerated. Speeding up the tool can be realised in various ways, e.g., by parallelising computations, running the load flow solver on GPUs, or using machine learning (ML) algorithms (see e.g. [12]). Moreover, we note that the extra objective (i) is important since it gives the operators more guarantees that switching busbar couplers is actually possible.

Finally, the GridOptions tool needs to be integrated into the larger landscape of decision support tools present in the control room. It is important to prevent a fragmented control room environment consisting of a diverse set of screens and tools which can lead to cognitive overload and decreased situational awareness [1]. To achieve this, it can help to apply frameworks for describing the interaction between human operators and autonomous, automated, and manual control systems [13]. Mapping out in detail the interactions of the operators and the decision support tools can feed back on the design of the decision support tool since sub-optimal design of human-machine interfaces and interactions can be a risk factor to human error in operations. Ultimately, the challenge is to create an AI assistant for power system operators [14] that provides iterative bidirectional communication, manages the operators cognitive load, and unifies all decision support in a single hypervision module [1]. The resulting hybrid intelligence can lead to true human-machine partnerships with synergetic interactions, where the human and the machine would continuously learn from one another, sharing knowledge and representations.

Specifications	(i) Make tool available at other times in the operational process (ii) Scale up to larger grid size (i.e. enlarge geographical scope)
Requirements	(i) Speed up computation by using ML (e.g. [12]) (ii) Day-ahead/intraday data is usually flawed due to e.g. forecast uncertainties. Hence, strategies should also be evaluated (a posteriori) using real-time snapshot data and the corresponding EMS load flow solver
Constraints	(i) Exclude switches that cannot be used remotely
Decision variables	(i) Line switching (ii) Phase-shifting transformers (PST) (iii) Redispatch
Objectives	(i) Voltage and phase angle deviations (ii) Dynamic Security Assessment (DSA) violations
Behavioural descriptors	(i) Geographical locations of redispatch, for example
Algorithms	(i) Include AC computation in the optimization (ii) Improve multi-objective optimization (e.g. [8-11]) (iii) Enlarge number of algorithms (ensemble approach)
User interface	(i) Provide visualization of entire network (ii) Include backend in dashboard enabling interactive load flow computations for more flexible action exploration (iii) Integrate the tool in the operator cockpit

Table 2 - Possible extensions of the GridOptions tool

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