Constraints for congestion-based transmission topology optimization

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***Abstract*—The integration of renewable energy sources increases congestion in transmission grids, driving up redispatch costs and carbon emissions. Transmission Topology Optimization offers a cost-effective solution by reconfiguring grid topology through strategic switching actions. While research highlights the potential of Transmission Topology Optimization, practical adoption is hindered by computational complexity and insufficient consideration of operational constraints. This paper bridges that gap by compiling a comprehensive set of constraints essential for real-world implementation in congestion management. Drawing on expert interviews with European Transmission System Operators, we identify constraints that ensure physical feasibility, N-1 security, voltage stability, and operational practicality. Key aspects include limiting branch currents without creating new congestions, minimizing switching actions, maintaining safe voltage angles and magnitudes, and coordinating with neighbouring grids. The list was compiled by presenting topologies to the operator, asking the question "would you switch this topology, and if not why?". By codifying the responses into operational constraints, this study accelerates the transition from theoretical models to practical solutions, enhancing grid flexibility and resilience under high renewable penetration.**

***Index Terms*—Transmission Topology Optimization – Optimal Transmission Switching – Network Topology Optimization – Congestion management – Operational Planning**

1. Introduction

The ongoing energy transition challenges the operation and stability of electric power systems. Wind and solar power generation is volatile [1] and power plants are often sited at remote locations leading to increased grid loads [2]. Congestion must be remedied by Transmission System Operators (TSOs) which can lead to substantial costs [3], [4]. For instance, redispatch and counter trading in the German transmission grid leads to costs of several billion Euros per year [5], [6]. Notably, redispatch also increases carbon emission when wind turbines are curtailed, and fossil power plants are ramped up.

Transmission Topology Optimization (TTO) can provide a cheap method to mitigate congestion and thus to reduce costs and emissions [7], [8]. The basic idea is to reconfigure switches, so that the path of least resistance is more beneficial according to the forecasted grid situation. In this way current flow through highly congested areas can be rerouted through less congested parts of the grid. These actions may not remove congestion completely but reduce it significantly such that costs for redispatch or counter trading decrease.

Several studies emphasize the potential of TTO in power systems with a high penetration of renewables [9], [10], [11]. However, the comprehensive adoption by transmission system operators is impeded by various factors [8]. First, finding the optimal grid topology is computationally hard [12], [13]. Second, many research studies do not capture the complexity and operational constraints of real transmission systems. Hence, the developed algorithms often identify topologies that appear highly promising in simulations but cannot be realized in reality.

This paper contributes to bridging the gap between research and applications of TTO for congestion management. While the aim of TTO is easily defined as the reduction in redispatch costs, operational and security aspects are harder to define and often result in a trade-off to the objective function [14]. To facilitate translation, we compile a comprehensive list of operational constraints and procedures that must be reflected in practice but are often overlooked in theory. We focus on applications in congestion management, noting that other applications of TTO as for instance voltage or stability remedial actions, are also discussed in the literature [8]. We are confident that this list supports the development of effective algorithms and software and simplifies the translation to applications.

2. Fundamentals and Background

In this section, we give a literature overview, review some technical and operational aspects of TTO, and define terms that are necessary for the formulation of operational constraints below.

2.1 Literature

This section provides a brief overview over research directions in TTO. One strand of research extends the established

DC optimal power flow to include TTO. Topology actions are encoded via binary variables, such that the problem becomes a mixed integer linear program [15]. It has been shown that already this highly simplified problem is NP-hard [12], [13]. The original formulation includes only two constraints: (i) upper and lower limits for the real power generation per unit and (ii) upper limits for the real power flow per branch in the N-0 reference case. Further approaches discuss how to include real power flow limits in the N-1 case [16], [17].

DC power flow is based on several approximation that can impede its application to TTO [18]. Hence, a second strand of research focuses on the inclusion of topology actions in an AC Optimal Power Flow (OPF) approach [19]. This type of algorithms can handle voltage constraints and generator reactive power limits in addition to line limits and generator real power limits. However, AC OPF is considerably more complex and computationally intensive, such that heuristic methods or approximations are intensively studied [20]. Comparative evaluations of DC versus AC OPF can be found in [21], [22].

Gradient-free algorithms offer an alternative to established optimum power flow algorithms. Evolutionary algorithms or more generally Quality Diversity (QD) algorithms are routinely used in power engineering [23], [24]. More recently, reinforcement learning [25], [26], [27], [28] and graph neural networks (GNNs) [29], [30], [31] have been proposed for TTO. Gradient-free algorithms are highly flexible but also face certain shortcomings. Generally, gradient-free algorithms are not guaranteed to find the optimum solution. QD algorithms can include almost arbitrary constraints but generally require large computational efforts. GNNs are very efficient, but constraint satisfaction cannot be guaranteed.

Notably, one can also design hybrid algorithms. For instance, it has been proposed to use machine learning models to deliver good starting points for AC OPF computations [32]. Similarly, one may use the result of a DC TTO as a starting point for a second-stage OPF. Furthermore, heuristic preprocessing steps can reduce the search space and thus speed up the optimization [11].

In conclusion, the development of algorithms for TTO is a highly active research field. Many studies focus on the theoretical and computational challenges, as TTO is NP-hard in general. System operators often lay a different focus as topologies must adhere to various security rules and to common operational practices. To bridge this gap and guide software development, it is necessary to codify the constraints.

2.2 Fundamentals of TTO and Notation

To recall the layout of a substation, we have plotted a typical substation layout of a fictive station in Fig 1 and Fig 2 using PowSyBl. In this work, we call switches that can switch under load a breaker, displayed with a box, and switches that cannot switch under load a disconnector, displayed as a cross or diagonal line. The assets connected to a substation are mainly powerlines and transformers, however reactive control elements such as Static Synchronous Compensators (STATCOMs) or large generators/loads can also be directly connected to TSO busbars. Each asset is connected through an asset bay, which consists of one disconnector per busbar. The busbars are connected through busbar couplers. Complex busbar couplers include horizontal disconnectors. The concrete substation layout varies from station to station and might be fundamentally different between TSOs. We plot a simple two-busbar single-coupler layout and one more complex three-busbar three-coupler layout. The latter would typically be used for larger stations with 10-30 connected circuits. The simple station supports a two-node operation with two electrically separated busbars, while the larger one technically supports a six-node operation. In practice, two-node operations are dominant.

Generally, TTO is concerned with operating switches on the transmission grid, the categories of actions available can be divided into four major categories

1) Disconnection of a line or transformer, also called Transmission Line Switching. In this work referred to as disconnection.
2) Busbar reassignments inside a substation, done by switching the disconnectors in the asset bays.
3) Opening of one or more busbar couplers and potentially horizontal disconnectors.
4) Cancelling a maintenance and reconnecting a disconnected line, transformer or busbar.

While the categories 1 - 3 are non-costly, cancelling a maintenance is a costly operation. Categories 1 - 3 decrease the degree of meshing (unmeshing) of the grid and thus need a more careful approach, while increasing the meshing of the grid in 4 generally comes with few technical drawbacks except for the cost associated with rescheduling the maintenance. The constraints in this work thus mainly touch upon 1 - 3.

2.3 Integration into congestion management processes

Further actions in the scope of operational planning congestion management are

1) Setting of Phase Shifting Transformer (PST) taps (non-costly)
2) Setting of High Voltage Direct Current (HVDC) setpoints (non-costly)
3) Adjustment of generator and storage setpoints, also called redispatch (costly)

These are not strictly part of TTO, but any TTO solution must integrate with these, trying to find the cheapest and safest overall solution. Note that the goal of cost-saving can be counter-intuitive and is different from minimizing overload: a topology that shifts overloads to a part of the grid with cheaper redispatch, or even creates higher overloads in total, can make economic sense looking at redispatch costs. If such a topology is proposed, it must be well explained to the operator within the Human Machine Interface (HMI) framework.

We conclude this section with an important remark: Stepwise procedures typically translate constraints into objectives. For instance, TTO is applied in the first step to minimize constraint violations. Here, operational constraints are no longer

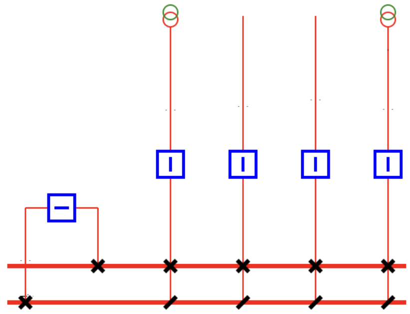

Fig. 1. A minimal substation layout, typical with up to 10 circuits

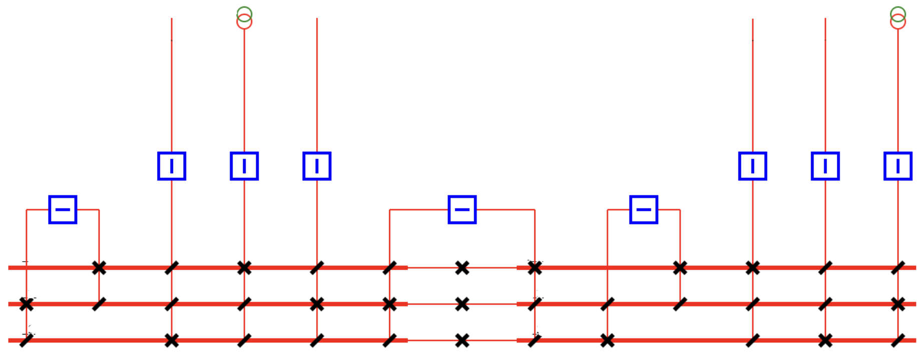

Fig. 2. A complex substation layout, typical for 10 to 30 circuits. For brevity, only plotted with 6 circuits here.

constraints in a mathematical sense but rather objectives. A second step will then remove all constraint violations, typically via generator redispatch. Operational constraints are equally objectives in a mathematical sense, such as the amount of switching required to reach a topology. Nevertheless we will stick to the term “constraints” in the following, adopting the operators’ viewpoint.

3. Methods

The aim of this paper is to provide a comprehensive list of operational constraints to guide the development of next generation TTO software. To compile this list, we have conducted expert interviews with control room operators responsible for the security of the transmission grid operated by 50Hertz, Elia Transmission Belgium and TenneT Netherlands. All these TSOs operate under a zonal market system.

We have conducted the expert interviews along concrete use cases to reveal constraints and procedures that are used in practice but not formally codified. Following this idea, we have presented one or multiple topology candidates to the operator and asked two questions: (i) Would the operator implement the respective topology? (ii) If not, why? The stated reasons for rejecting a topology were collected and translated into constraints that can be implemented in optimization algorithms. As details vary from grid to grid, we refrain from giving fixed numbers but formulate constraints in a general way that can be easily adapted. Finally, we have added commonly accepted constraints for the sake of completeness, as for instance transmission line limits.

4. Constraints

Fundamentally, TTO is a trade-off between grid capacity and stability. For every switching action that unmeshes the grid to create a more beneficial flow situation, there is always a decrease in stability associated through the lower degree of meshing. In this section we explain and discuss each constraint point individually in an informal way to give an intuition on this trade-off.

4.1 Reduce branch currents below admissible limits

The main aim of congestion management is to bring line and transformer flows at or below their admissible rating. In a zonal market setup, the market is not guaranteed to provide a feasible dispatch. Viewing TTO as a process within congestion management, the aim of TTO is to use available and safe topology measures as cost-effectively as possible.

4.2 Do not bring previously lightly loaded assets close to their operational limits

Under TTO, the aim is to shift the flows in the grid. Naturally, this can also result in new branches approaching overload currents. Together with forecast inaccuracy, this can form new congestions, which is especially problematic if the number of congestions increases. In non-stochastic TTO, a deadband below 100% can be used where a penalty is incurred if branch loads rise within the band. This way, as long as forecasting errors are smaller than the deadband, the optimizer incurs a penalty for creating more congestions.

4.3 Switch only what is physically feasible and reachable

All switching actions should be feasible in the full node/breaker realization of the grid. Note that a substation can easily hold several hundred switches, so naive enumeration is not feasible. Also as discussed in Sec 4.6, only topologies that can be reached by a feasible switching order must be proposed. Furthermore, some switches may require manual operation and can only be included in TTO if there is enough time to send service personnel to implement the switching. Disconnectors cannot be switched under load.

Equipment under active maintenance must not be switched on. An exception is to cancel planned maintenances, as discussed in Sec. 4.15. Some maintenance requirements may dictate one of the busbars to be kept free to assist in disconnection of elements. Furthermore, there can be other operational reasons to exclude a station or sections of a station from switching.

4.4 Minimize the number of switch operations necessary to reach a topology

A measure of topology distance can be defined as how many individual switch actions away

1) from the well-understood fully connected grid state
2) from the previous grid state

does a topology reside. This is largely determined by the number of open breakers, but also the disconnector switching actions done. Multiple operational reasons require the minimization of both quantities. Each switching action requires operator work in the SCADA system, can fail, and moves away from the well understood fully meshed configuration. Thus, unnecessary switching must be avoided. No concrete number can be set for this a-priori, hence a human-machine interaction needs to be used where the human can decide on feasibility based on the situation at hand in the control room. Also, a minimum switching sensitivity for breaker openings can be defined, where breaker openings that cause a minimal congestion reduction shall be omitted. Generally, there should be a stronger incentive to minimize breaker openings than to minimize disconnector toggles. While more complex stations such as the station in Fig 2 support many separated electrical nodes, even for the larger stations a two-node or at most a three-node operation is desired to keep operational workload low.

4.5 Perform the operation time-coupled

The question behind topology optimization is not only which switches to switch, but also when to switch them. The time dimension can be further separated into a coarse decision of finding the time of the day when to open which breaker, and a fine decision of in which order to actuate each switch as discussed in Sec. 4.6.

In the coarse decision, a start- and an end-time for every open breaker is required. Aim is to keep the opening times as short as possible but long enough to cover the entire congestion situation. As a heuristic, instead of actually performing a time-coupled optimization, it can be sufficient to identify the peak of the congestion and only optimize the worst timestep for each congestion, as topologies tend to hold a few hours before and after the peak.

4.6 Propose the safest switching order

The order in which switching happens generally matters but can be excluded in operational planning. Generally, all disconnectors must be switched before the breakers with a few exceptions in complex couplers. Breakers should be switched in an order that is safe according to voltage, voltage angles and branch flows at every point. Furthermore, breaking currents should be as low as possible and shall always be below breaker limits.

4.7 Ensure all constraints hold under N-1

Transmission grids in Europe are operated with the principle of N-1 security. This means that the failure of any element of the grid must result in a safe operating state. This includes every line, transformer, generator block, load, reactive compensation device and shunt in the grid. N-1 safety also includes pylons, switches, busbars and power plants, though only when they are explicitly added as exceptional contingencies. The cost of redispatching these elements combined with the low failure probability means that a risk-based assessment is made whether they should be part of the N-1 definition or not. Weather, age, threat intelligence and other factors play into this risk assessment. Busbars are separately discussed in Sec. 4.8. Entire substations or voltage levels are typically not included in the N-1 definition.

Without further elaborating, we imply that all constraints have to hold in both N-0 and N-1, specifically Sec. 4.1, 4.2, 4.6, 4.9, 4.10, 4.11, 4.12, 4.13. Furthermore, the full observation area with all N-1 constraints has to be computed.

4.8 Consider busbar outages

Busbar outages are a type of N-1 constraints that occur rarely, but with high grid impact. Hence, busbar outages are only healed on demand as exceptional contingencies. However, when finding a topology, it is paramount that no single busbar outage can decisively split the grid. For the sake of optimization, this means that either a do-not-make-it-worse type of constraint that compares to the pre-optimization grid needs to be employed or a set of heuristic rules that resemble the thinking of operators. These heuristic guidelines could include *'place approximately the same amount of power on each busbar'* and *'parallel circuits should be placed on different busbars'* and must be discussed with operators for each substation.

4.9 Keep voltage angle differences within safe limits

If the voltage angle across an open breaker exceeds a certain threshold, the breaker cannot be closed again as the phase jump would trip connected equipment. This must be avoided so that operators have the option of returning to the fully connected grid at any time without risking pole slip or similar transient problems. No open breakers should have a voltage angle larger than this threshold across them, both in N-0 and N-1.

Furthermore, open busbar couplers in a series of adjacent stations can easily lead to voltage angle divergence across the formed corridor split, even if the load flow does not present it. Hence, the number of adjacent splits must be limited.

4.10 Keep voltage magnitudes and jumps in permissible range

A situation in which topology brings the grid into a state which cannot be recovered by subsequent operational voltage control processes is to be avoided. This is especially critical when extensive unmeshing brings the grid close to voltage collapse as discussed in Sec 4.11, but also voltage band or voltage jump violations shall be kept within limits. Equipment will trip if operated out of band or exposed to strong jumps.

Voltage band violations are violations where the voltage in N-0 or N-1 is outside of a permissible band around nominal voltage. As high-voltage violations can often be healed in a subsequent voltage control process, the upper limit can be relaxed slightly during TTO. If the lower limit is violated, it is not clear whether this is due to poor setpoints or imminent voltage collapse, thus a strict boundary seems more appropriate. Additionally, in N-0, a safety margin to the band limit might be required by the TSO.

Voltage jump violations are defined as a too high voltage difference due to a switching transient or due to an N-1 case. These violations cannot be healed as easily in a voltage control stage, hence a hard limit is required.

Topology can also be used as a voltage remedial action. Disconnecting lightly loaded lines or using lines connected on only one side as a capacitor is possible, but out of the scope of this work.

4.11 *Keep lines away from voltage collapse*

Voltage collapse is defined as the extremum point in the P-V curve of a branch [33], also called nose-curve due to its shape. If a branch or corridor is loaded up to its voltage collapse point, it consumes exponentially more reactive power which drops the voltage to the point that no more active power can be transferred. Typical voltage control measures such as capacitors or generator setpoints are unable to stabilize the grid under these conditions. Only an active power redispatch or re-meshing of the grid can bring a branch significantly further away from voltage collapse. Unmeshing as in topology optimization can bring a branch closer to its voltage collapse point. Any TTO solution must hence check for voltage collapses. Heuristically, if voltage collapse is imminent in a corridor, then the entire grid area can be blacklisted for unmeshing a priori.

4.12 *Minimize rerouting of flows through neighbour grids*

A transmission grid usually has vertical (Distribution System Operator (DSO)) and horizontal (TSO) neighbours with separate congestion management processes. When performing a topology optimization, the impact on these neighbours has to be assessed.

On the TSO level, at least two hops into the neighbour grid are sensible to monitor in the computation. Switching actions tend to have wider sensitivity areas than redispatch and using grid reductions too aggressively will hide flow-rerouting effects. Also, the neighbour N-1 cases that are one hop away have significant effect. More holistically, also the problems of the neighbour grid could be healed if a larger optimization area is employed.

With both meshed and unmeshed DSOs, care must be taken to not disturb the operations of the respective DSO. The following scenarios should be avoided, even if they are within the thermal spec of the transformers:

- A soft coupler scenario where the high-voltage busbar coupler is open and the transformers on each side of the coupler feed in opposite directions.
- A large jump in transformer loading before/after optimization. This is both relative (e.g. do not increase from 10% to 90%) and absolute (e.g. do not inverse the flow from 50% up to 50% down).
- A large jump in transformer loading from N-0 to N-1, both relative and absolute.

These restrictions are necessary to ensure the separate operation of the DSO grid without needing to adjust to the needs of the TSO but can be violated in exceptional cases after extensive discussion with the DSO.

4.13 *Ensure short-circuit currents are within bounds*

As a rule of thumb, unmeshing of the grid reduces short circuit currents and meshing of the grid increases them. The general trend in the grids of this study is towards too high short circuit currents. Increased grid extension naturally meshes the grid more, driving up short circuit currents. Also, installed power is expected double in 10-15 years [34]. Despite the lower short circuit contribution of inverter based resources, this still results in a net rise.

In our experimentation, we found it sufficient to check for short circuit violations post-optimization. However, future topology optimization approaches could even use short circuit limits as an objective, using unmeshing of the grid to jointly lower redispatch and short circuits.

4.14 *Use curative actions according to risk profile*

A curative switching action is a switching rule that is not executed preventatively but only in case a specified N-1 case actually happens. This has two fundamental advantages: The topology can be specialized to the outage case and the preventative topology must only adhere to the Temporary Admissible Transmission Loading (TATL) loading under N-1. The main disadvantage is the higher risk associated with curative actions. After applying the curative action, the grid must be N-0 safe according to the Permanently Admissible Transmission Loading (PATL). Also, the constraints from Sec 4.2 and 4.5 can be ignored for curative actions.

4.15 *Take into account cost and rescheduling options when cancelling maintenances*

One of the remedial actions available during topology optimization is the cancellation of planned maintenances. This is the only costly topological action available. To be able to cancel a planned maintenance, three requirements have to be met

- The maintenance must be cancellable, which means it is of lower criticality and works haven't started yet.
- An alternative timeslot for the maintenance needs to be available.
- The redispatch cost saving of the cancellation has to outweigh the increase in redispatch cost on the alternative timeslot plus the costs of restarting the maintenance preparations (e.g. ordering cranes).

Under these circumstances, cancellation is possible. While the redispatch cost criterion is objective and can be estimated using long term forecasts, the other two points are operational questions. Hence, it is more sensible to answer the question of how much redispatch costs every cancellation or combination of cancellations can save within TTO and leave the yes/no decision to the operator.

4.16 *Account for uncertainty of the forecasts*

In European day-ahead congestion processes, the grid situation is determined by market results and forecasts. Market results can change due to intraday trades and forecasts come with an uncertainty. As a result, a point estimate of the grid situation is inaccurate by definition. A minimal stochastic TTO solution optimizes for mean and worst-case overloads at the same time. A more advanced system might provide multiple topology proposals based on different stochastic realizations and consider the risk associated with each.

4.17 *Complete the optimization timely*

The maximum tolerable runtime and available computational resources are dictated by operational processes. Generally, a lower runtime will facilitate more time for human review. To aid an operational tool, a slow pre-optimization stage can be employed which runs before receiving the market results, forecasts and maintenances on just the master data grid.

4.18 *Minimize grid losses*

Unmeshing the grid naturally increases its impedance, and with that the grid losses. Hence, there is a natural cost/benefit trade-off. Redispatch costs tend to be higher than grid losses (Germany 2023: 3.2 billion € redispatch, 1.3 billion € grid loss [6]), however the current assumption is that the positive impact of topology on redispatch costs outweighs its drawbacks on grid losses.

5. Conclusion and outlook

This work compiles a list of operational constraints for topology optimization, giving an aid for implementing a TTO system applicable in the congestion management process. Generally, TTO sits at the cost-safety trade-off that is inherent to any TSO business. Switching actions drastically change the dynamics of the grid and have a major impact on both safety and costs. To correctly identify the safety impact, the list of constraints in this work can serve as a reference. We leave quantifying the cost impact to later works.

Concrete priorities and values for discussed constraints have to be set in discussion with the TSO according to the operational risk profile. Furthermore, some circumstances such as operator workload are hard to encode in an optimization, which is why a HMI that is capable of balancing the priorities must be part of any TTO system.

The present work considers TTO primarily from a static, steady-state perspective. Dynamic and transient stability aspects are not included, as such assessments are not fully established in the operational planning of the TSOs under study at the time of writing. A final security assessment of candidate topologies should nevertheless account for these aspects, which will further increase the computational burden. For an implementation, a prioritization and effective use of heuristics is therefore required to tackle computational complexity, so that TTO on full scale becomes feasible. Furthermore, some of the constraints discussed above may require adaptation in grids with a high share of inverter-based resources. For instance, when assessing minimum short-circuit current levels, reactive current contributions from inverter-based resources may only be sustained for a limited time and should be treated accordingly. Finally, all TSOs involved in this study have a zonal market, and TTO in Location Marginal Pricing (LMP)-style markets might have different constraints or priorities.

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Appendix 1
Example Values for Constraints

In Table 1, we present some example values that are present in the operational processes of one of the TSOs in our study. While concrete values will vary, these can serve as a starting point for a TTO implementation project.

TABLE 1
EXAMPLE VALUES FOR OPERATIONAL CONSTRAINTS

Constraint	**Value**
Loading Deadband (4.2)	90% - 100%
Voltage band (4.10)	±10%
Voltage jump (4.10)	±5%
Max voltage angle across switch (4.9)	15 deg
Max adjacent bus splits (4.9)	2
Max open busbar couplers in grid (4.4)	8
Max DSO transformer loading jump (4.12)	±30%
Curative TATL time/loading (4.14)	30 min/113%
Maximum TTO runtime (4.17)	15 min
Minimum breaker sensitivity (4.4)	50MW
Observation area (4.7)	2000 el. buses, 3000 N-1 cases
Forecast resolution (4.5)	15 min
Min distance to voltage collapse (4.11)	200MW