21, rue d'Artois, F-75008 PARIS
http://www.cigre.org

CIGRE US National Committee
2019 Grid of the Future Symposium

# Application of Topology Optimization in Real-Time Operations

**J. CASPARY, D. BOWMAN, K. DIAL, R. SCHOPPE, Z. SHARP,
C. CATES, J. TANNER**
**Southwest Power Pool**
**USA**

**P. A. RUIZ**
**New Grid, Inc., The Brattle Group and Boston University**
**USA**

**X. LI**
**New Grid, Inc.**
**USA**

**T. B. TSUCHIDA**
**The Brattle Group**
**USA**

## SUMMARY

Congestion management in power systems is a critical and complex task of system operations. Its cost impacts can be substantial: The cost of congestion totals US$3-6 billion annually in the United States alone. As more variable energy resources are added to the system, congestion management is likely to become more challenging as the variable and low-cost generation makes network flows more dynamic and increases the price differences between them and traditional generation. In future systems, congestion management may incur higher costs and may have higher emissions impacts.

The main approach to managing congestion is to redispatch generators. While this approach can be effective, it replaces output from the more economical generators by more expensive generation. Hence, it leads to higher costs of electricity for end-consumers.

A complementary approach to generation redispatch is topology optimization, which reduces congestion by reconfiguring the transmission system to redirect power flow from congested facilities to uncongested facilities. Currently, system operators employ this approach by identifying reconfigurations based on their knowledge and experience with the system. While this approach can be very effective, its use is limited due to the difficulty of promptly finding beneficial network reconfigurations based on operator knowledge.

jcaspary@spp.org

Topology optimization software aims to make the task of quickly identifying beneficial reconfigurations effortless.

This paper reports on a study and a pilot to evaluate the effectiveness of topology optimization on Southwest Power Pool's (SPP) system.

The study evaluated 20 historical snapshots of the SPP system from real-time operations representing different complex system conditions with severe congestion. Topology optimization software was used to identify several reconfiguration solutions for each snapshot, validated by SPP in the Energy Management System (EMS) for operational feasibility. Topology optimization software found feasible beneficial reconfigurations for 95% of the historical snapshots evaluated, which provided an average of 31% flow relief on the constraints of interest. In addition to meeting typical SPP operating criteria, SPP defined a set of more stringent criteria for what constitutes a preferred reconfiguration. Preferred reconfigurations were found for 70% of the snapshots and provided 26% flow relief on average. If topology optimization is fully deployed in SPP real-time operations, the study estimates the congestion cost savings in SPP could be in the range of $18-44 million a year.

In the pilot program, SPP used the *NewGrid* topology optimization software to study its effectiveness in managing congestion identified during real-time operations. Out of 100 congested constraints from real-time operations, 55 preferred solutions were found. Notably, two of the constraints were studied in support of SPP's real-time operations, and the solutions identified were implemented by SPP. Both solutions eliminated the overloaded constraint without introducing new overloads.

SPP is also evaluating the use of topology optimization to support long-term planning efforts. For three severe multiple-contingency events in which the current Corrective Action Plan (CAP) is to shed a substantial amount of load (redispatch is ineffective), topology optimization software found reconfigurations that relieved the overloads without additional overloads or any load shed.

**KEYWORDS**

Topology Optimization, Congestion Management, Reconfiguration, Market Efficiency

## 1. Introduction

Congestion management in power systems is a critical and complex task of system operations. Its cost impacts can be substantial: The cost of congestion totals US$3-6 billion annually in the United States alone [1]. As the generation mix evolves, increasing the penetration of wind and solar resources, congestion management is likely to become more challenging. New technologies continue to make network flows more dynamic and drive price differences between new resources and traditional generation. In future systems, congestion management may incur higher monetary costs and also have higher emissions impacts.

The traditional approach to managing congestion is to redispatch generation, thus varying the production-consumption pattern of power on the network. While this approach has been effective, it can displace output from more economical generators with more expensive resources. Hence, it often leads to higher costs of electricity for end-consumers, as indicated above. With potential rate fatigue as the result of developing new transmission, it is critical that system operators get the most value out of the current infrastructure.

A complementary approach to generation redispatch is topology optimization, which reduces congestion by reconfiguring the transmission system. As a result, power flow is diverted from congested facilities to uncongested facilities. Currently, system operators employ this approach on an ad-hoc basis, identifying reconfigurations based on their knowledge and experience with the system. In the Southwest Power Pool (SPP), this has primarily been utilized from a reliability perspective when few other options of redispatch remain. While this approach can be very effective, its use is limited due to the difficulty of promptly finding beneficial network reconfigurations based on operator knowledge.

*NewGrid Router* is a software solution developed to perform topology optimization studies and helps to quickly identify possible reconfiguration solutions. The software identifies and prioritizes reconfiguration solutions to take advantage of grid flexibility and provides alternative mechanisms for congestion relief. Contingency evaluation then assesses the feasibility of solutions from a reliability perspective to ensure no new reliability issues are imposed by the solution. Preventive solutions requiring reconfiguration in the base case are identified along with corrective solutions requiring reconfiguration if the contingency were to occur.

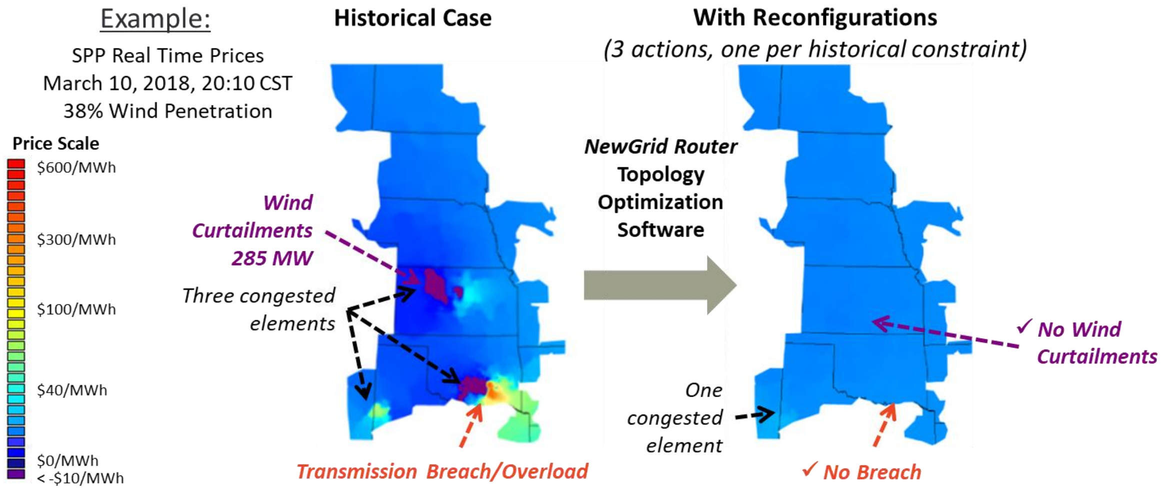



**Figure 1 : NewGrid Router Topology Optimization Example**

Figure 1 shows a test case simulation on a historical case from SPP. *NewGrid Router* was able to successfully identify three switching actions (one per historical binding constraint) that resulted in no breached constraints (loading over 100%). Additionally, in this scenario, the additional transfer capacity realized by the switching actions eliminated the need to curtail 285 megawatts (MW) of wind output in the base case.

## 2. SPP Operations Study

SPP, NewGrid and The Brattle Group conducted a study to evaluate the effectiveness of topology optimization in supporting congestion management on SPP's system. The study evaluated 20 historical snapshots of the SPP Energy Management System (EMS) from real-time operations, selected by SPP, representing different complex system conditions with severe congestion with at least one constraint, also identified by SPP. The *NewGrid Router* topology optimization software was used to identify several reconfiguration solutions for each snapshot while keeping the same generation dispatch and meeting operating criteria. The solutions were validated by SPP in the EMS for feasibility and their impact on congested constraint flow mitigation, and are labeled as feasible once validated. EMS validation also included executing contingency analysis with the reconfiguration in place. **Error! Reference source not found.** shows the location of the 20 constraints analyzed in the study, including the constraint definitions and the level at which they were binding.

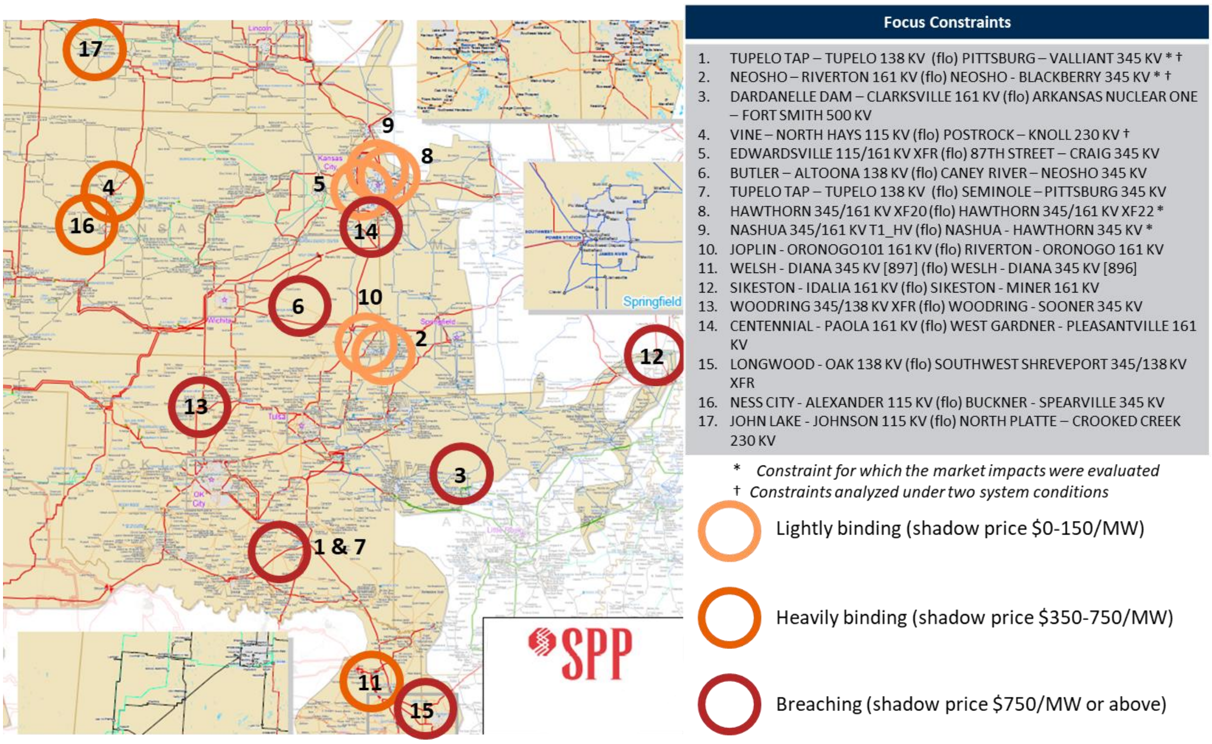



**Figure 2 : Location of Constraints Analyzed**

The following SPP criteria were used for the reconfiguration search in the study:

- Reconfigurations must not lead to new constraints loaded above 95%, on both pre- and post-contingency scenarios.
- Reconfigurations must not lead to voltage violations, on both pre- and post-contingency scenarios.
- Reconfigurations must not radialize more than 30 MW of load.
- Reconfigurations were limited to three switching actions.

Also, the following SPP criteria were used to define preferred reconfigurations:
- Consist of a single switching action.
- Switch a transmission facility with nominal voltage of 230 kilovolts (kV) and below.
- Provide at least 10% relief.

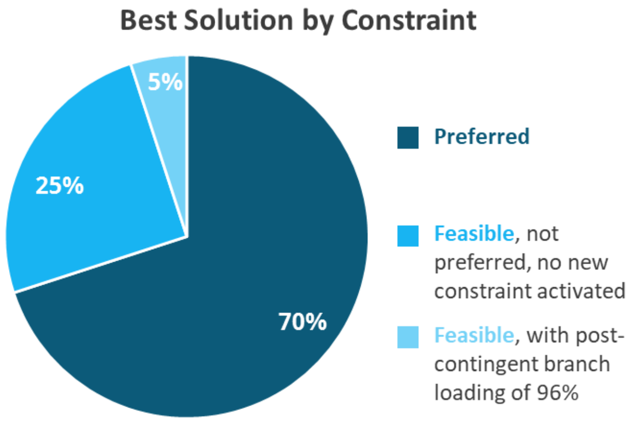



**Figure 3 : Best Solution by Constraint**

As shown in Figure 3, the study found reconfigurations meeting SPP criteria for 95% of the historical snapshots (19 snapshots out of 20). The remaining snapshot reconfiguration led to a new constraint loading at 96% (while providing over 10% of flow relief on the previously violated constraint). As shown in Figure 4, these feasible reconfigurations provided 31% flow relief on the identified constraints. Also, the study found at least one preferred reconfiguration for 70% of the historical snapshots (14 out of 20). Such preferred reconfigurations provided 26% flow relief on average. Note that the resulting reconfigurations met all operating criteria set forth by SPP, as validated by SPP engineers using the EMS. In addition, all reconfigurations were found in between 10 seconds and 2 minutes using an off-the-shelf server. For reconfigurations that result in newly radialized load, service reliability is degraded, which must be considered.

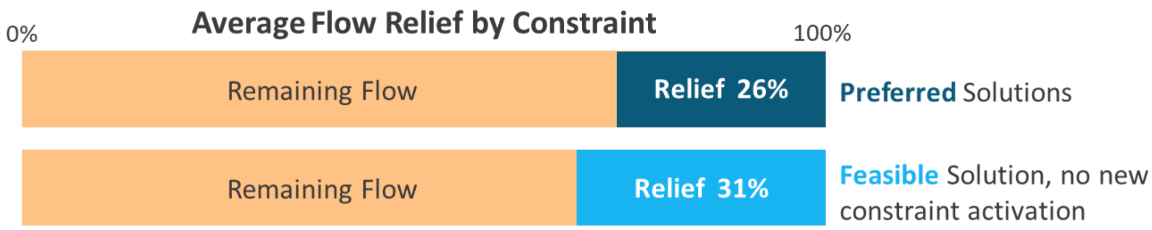
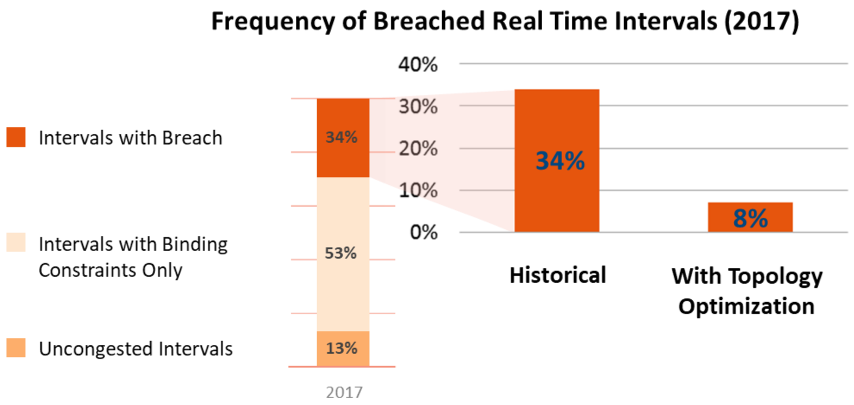



**Figure 4 : Average Flow Relief by Constraint**

If topology optimization is fully deployed in SPP real-time operations, the study demonstrates (see Figure 5) that the frequency of intervals in which a constraint is breached (overloaded) is significantly reduced. Based on SPP historical data from 2017, 34% of the real-time intervals had at least one breached constraint. With topology optimization, the study shows the frequency would be reduced to 8%.




Sources:
Historical: SPP State of the Market Report 2017.

* *This is a conservative estimate, as in the study of the 20 selected historical constraints, 95% of them were relieved to well below their limit.*

**Figure 5 : Reliability Benefits - Breached Constraint Relief**

Results discussed thus far have assumed that historical dispatch was not adjusted after the reconfiguration. In reality, the constraint relief could provide additional transmission system capacity for market utilization, providing potential market savings. This includes redispatching units based on economics, which may result in lowering, or even eliminating, wind curtailments.

As part of the study, four of the 20 constraint snapshots were selected to assess real-time market savings:

- TUPELO TAP – TUPELO 138 KV (flo) PITTSBURG – VALLIANT 345 KV
- NEOSHO – RIVERTON 161 KV (flo) NEOSHO - BLACKBERRY 345 KV
- HAWTHORN 345/161 KV XF20 (flo) HAWTHORN 345/161 KV XF22
- NASHUA 345/161 KV T1_HV (flo) NASHUA - HAWTHORN 345 KV

For these cases, real-time markets were simulated and benchmarked against historical dispatch and prices. Savings were calculated by comparing the dispatch and associated costs before and after reconfigurations. A subset of units (25-85 of 200-250 market dispatchable units) had their dispatch fixed to meet the benchmark. If these units were dispatchable, the savings could be even greater. Thus, the results obtained serve as a lower bound and should be considered as a conservative estimate. The real-time market savings are about 3% of the historical real-time congestion rent, based on the four cases evaluated. Using the historical real-time market congestion, the extrapolated market efficiency benefits (congestion cost savings) in SPP could be in the range of $18-44 million a year.

## 3. SPP Operations Pilot Project

SPP operations conducted a pilot with the *NewGrid Router* topology optimization tool between July and December 2018, concentrating on reliable operation of the transmission system. The pilot used the same SPP criteria as the study discussed in Section 2, except that preferred solutions in the pilot required a minimum 5% N-1 loading reduction (the study used 10% minimum relief).

Of 100 congested flowgates in real-time operations analyzed in the pilot, 55 preferred solutions were found. Notably, two of these solutions were utilized in real-time operations. One example concerns the mitigation of the DARCLAANOFTS permanent flowgate.

On Aug. 9, 2018, SPP operations experienced a post-contingent overload on the DARCLAANOFTS permanent flowgate. This constraint is challenging to control due to significant external parallel flow impacts. Real-time staff requested operations support to perform a topology optimization assessment for this constraint. Operations support quickly identified a pre-contingent mitigation plan that reduces the constraint flow by over 20% and eliminates the post-contingent overload. Figure 6 shows the mitigation of opening up Clarksville – Little Spadra Creek 161-kV line pre-contingent.

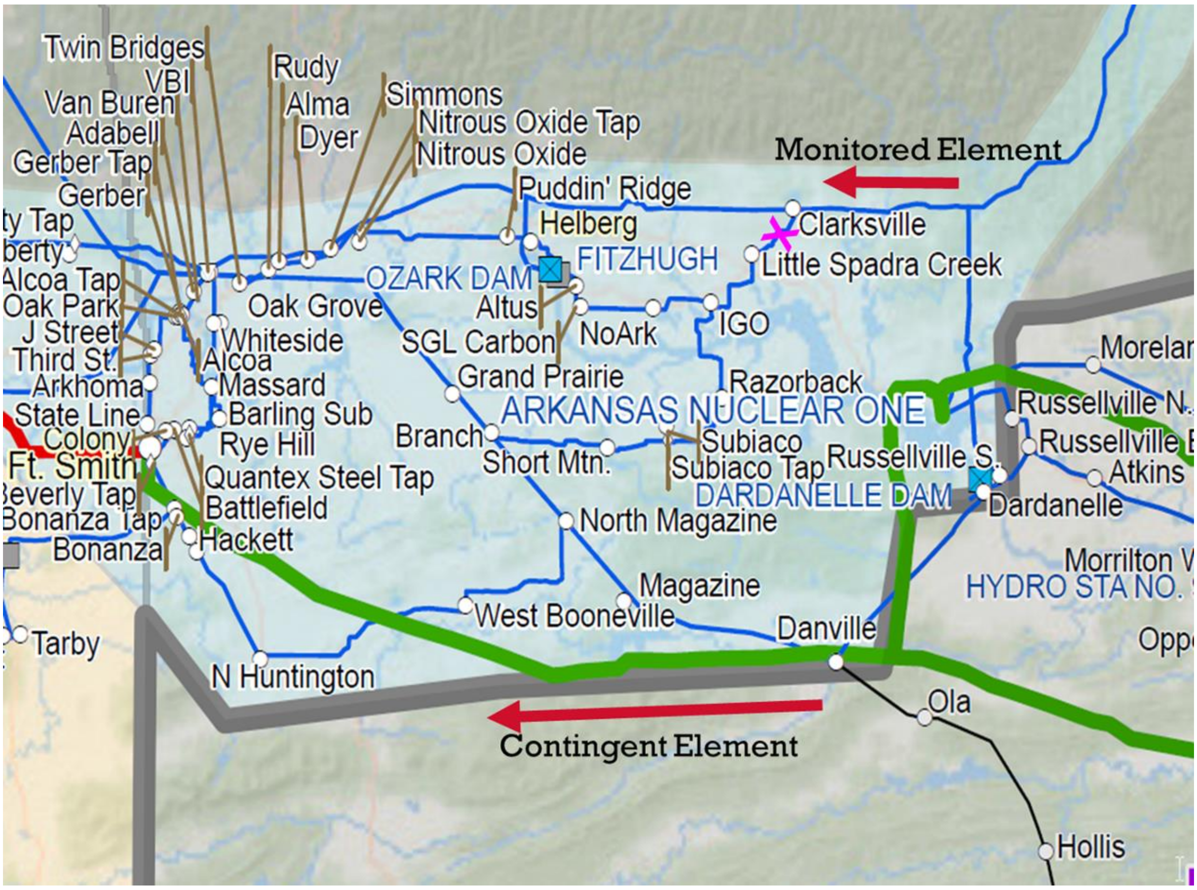



**Figure 6 : DARCLAANOFTS Mitigation Example**

SPP also found *NewGrid Router* effective as a means to ensure existing mitigation plans were optimal. SPP simulated several constraints and verified that the mitigation solutions found by the tool were comparable to the currently documented mitigation solutions being used in real-time operations. For a subset of constraints studied, *NewGrid Router* identified the same solutions as existing SPP mitigation plans.

A notable case studied with *NewGrid Router* evaluated congestion during high wind-penetration intervals. SPP transmission can be exposed to heavy transfers of wind generation during low load conditions. These transfers typically flow from west to east across the SPP footprint. Constraints exposed to these system transfers and remotely located from generation can be difficult to control, as generation shift factors are too low for the market to effectively redispatch resources to relieve the constraints. The constraint of focus, in this case, was Stonewall – Tupelo 138 kV (flo) Pittsburg – Valliant 345 kV, as shown in Figure 7. *NewGrid Router* found a reconfiguration of opening Civit – Stratford 138 kV, resulting in 24% relief on the constraint while limiting newly radialized load to less than 10 MW.

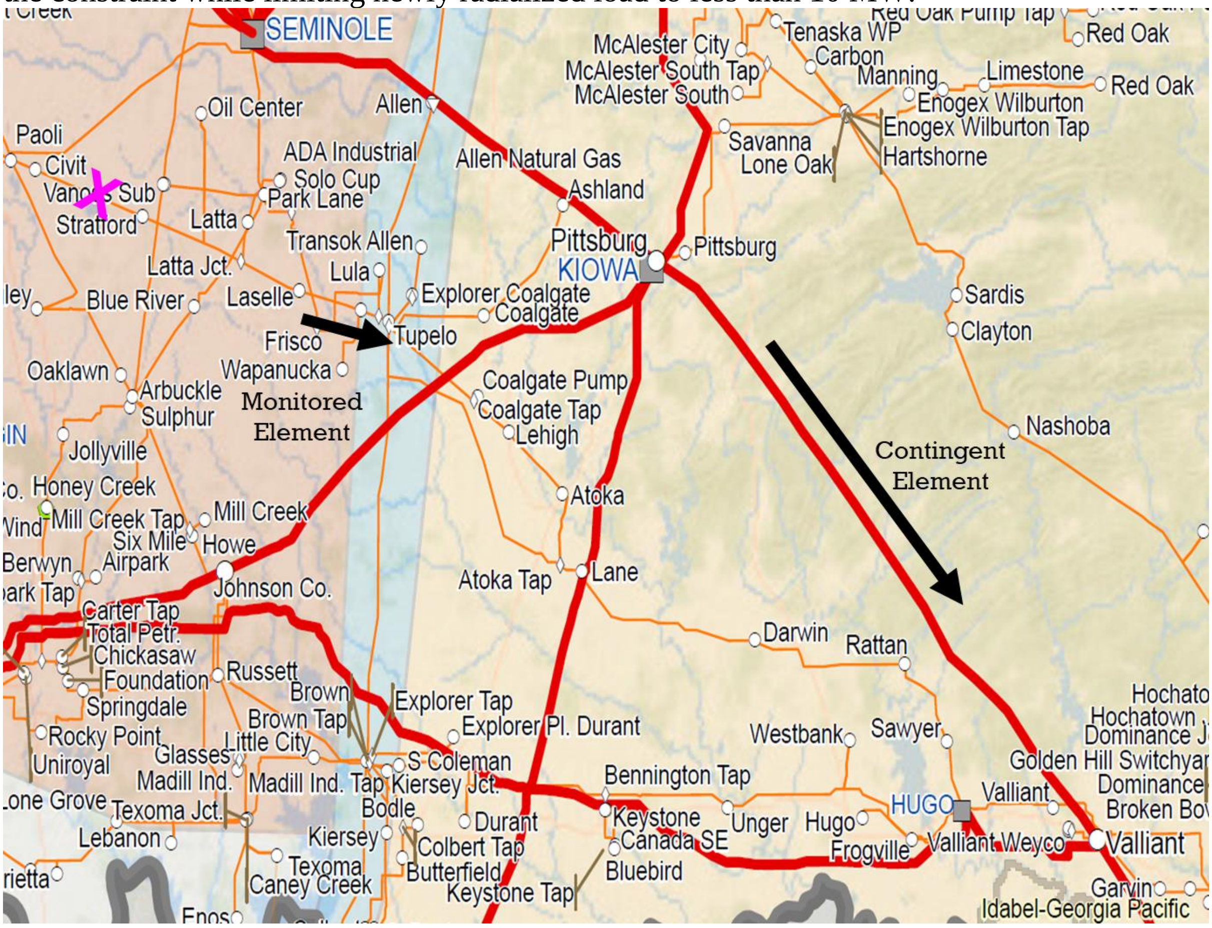



**Figure 7 : Stonewall – Tupelo 138 kV (flo) Pittsburg – Valliant 345 kV Mitigation Example**

## 4. SPP Planning Study

SPP also evaluated *NewGrid Router* for a long-term planning study, focusing on avoiding nonconsequential load loss. The North American Electric Reliability Corporation (NERC) allows load shedding as part of the Corrective Action Plan (CAP) for specified planning events involving multiple transmission outages that would otherwise result in NERC TPL-

001-4 violations [2]. SPP identified three specific severe multiple-contingency events for which existing CAPs rely on substantial load shedding (redispatch is ineffective):

- P6 Event involves two sequential, overlapping single contingencies.
- P7 Event is a multiple contingency resulting from a common structure or other single failure.
- Extreme Events include loss of a transmission corridor, an entire substation or power plant, or multiple elements due to a regional event or critical cyberattack.

Table 1 shows that *NewGrid Router* found corrective reconfigurations for all three cases that relieved the violations without additional violations or load shedding.

| Case Study Type | Flow on Violated Branch Initial [% of Rating] | Flow on Violated Branch With Solution [% of Rating] | Avoided Load Loss [MW] | No. of Actions | No. of New Constraints >95% flow | No. of New Constraints >100% flow | No. of New Constraints <0.9 pu volt | Radialized Load [MW] |
|---|---|---|---|---|---|---|---|---|
| P6 Event | 129% | 86% | 243 | 2 | 1 | 0 | 0 | 65 |
| P7 Event | 107% | 94% | 55 | 2 | 0 | 0 | 0 | 0 |
| Extreme Event | 113% | 97% | 151 | 1 | 1 | 0 | 0 | 0 |

**Table 1: Avoiding Non-Consequential Load Loss for Severe Contingency Events in Planning Studies**

## 5. Conclusions

Topology optimization is effective at routing flow around congested/overloaded transmission facilities. *NewGrid Router* performs this task efficiently, allowing the possibility for use in real-time operations to improve grid resilience. Looking forward, as flow patterns are changed by increased renewables, retired legacy thermal units and pockets of high load growth, this tool can be used to adapt system reconfigurations to manage congestion.

Topology optimization can be of benefit in many aspects of operations and markets. Operations planning/outage coordination can use this approach to mitigate expected congestion due to planned outages. Day-ahead operations and market optimization (and Transmission Congestion Rights/Financial Transmission Rights markets) may find optimization tools effective in co-optimizing resource (and transfer) schedules with transmission topology. Real-time operations and market support can use the tool to mitigate congestion due to system conditions that deviate from day-ahead plans.

Long-term planning studies can also benefit from using topology optimization software as support. The study presented in this paper found topology optimization very effective to minimize nonconsequential load loss in Corrective Action Plans (CAP) for severe contingency events. Future work in this area will research topology optimization approaches to select candidate transmission projects to relieve N-1 contingency violations and increase transfer capacity across constrained interfaces.

## BIBLIOGRAPHY


[1] Rob Gramlich. "Bringing the Grid to Life," Working for Advanced Transmission Technologies. [Online]. Available: https://watttransmission.files.wordpress.com/2018/03/watt-living-grid-white-paper.pdf

[2] NERC Standard TPL-001-4 — Transmission System Planning Performance Requirements.