Visualization Methods for Quickly Understanding the Evolution of Power Flow Constraints under AC Contingency Analysis

I. ANSELMO
620230348
Power Systems Engineer
Telos Energy Inc.
Professional with 10 years or less experience
isabela.anselmo@telos.energy

SUMMARY

Understanding and quickly assimilating the vast tables of results generated by AC contingency analysis tools is laborious and time-consuming today. In addition to the volume of data, it is not easy to connect relevant results in a tabular format, making it challenging for engineers to comprehend the findings and identify effective mitigations. This analysis aims to address this data presentation problem by employing visualization techniques developed to present the data plainly and emphasize the data connections that reflect power system connections. The developed method was applied to an analysis of the power system in the State of Michigan to examine the effects of the increasing levels of renewable penetration in conjunction with power transfer exchanges with MISO, PJM, and IESO, as well as the complexity introduced by having a completely PAR-controlled interface with IESO.

The steady-state analysis was conducted using AC power flow and contingency analysis in PowerGEM's TARA software. The models developed included the 2025 base Summer Peak and Shoulder cases (with 40% of wind dispatch) from MISO's Transmission Expansion Planning 2020 (MTEP20). The new models considered four conventional plant retirements, including plants already retired in 2022 and the planned retirements to be completed by 2025. Using the 2023 MISO Generation Interconnection Queue, areas and zones of potential renewable generation were identified. Finally, large-scale transmission system projects were considered, such as LRTP Tranche 1 (Long Range Transmission Planning: Tranche 1), to define all pathways of power transfer to Michigan.

Power transfer and contingency analysis were conducted using the developed models which reflect the expected Michigan power grid in 2025. First, for the purpose of determining the state's capacity import limit, the system-peak model dispatches more generation outside of Michigan (source region) and less generation inside Michigan (sink region), also known as a generation-to-generation transfer. As a result, more energy flows into Michigan, bringing attention to transmission limitations that further restrict imports. The evaluated source regions are the areas that border Michigan electrically: American Electric Power - AEP (PJM), American Transmission Systems, Incorporated - ATSI (PJM), Northern Indiana Public Services - NIPS (MISO), and Ontario (IESO). Due to its limited size (200MW), the back-to-back DC link to the upper peninsula of Michigan was not taken into account in the present study, which instead concentrated on the lower peninsula.

Once the power transfer analysis was completed, the contingency analysis was conducted, considering N-1 scenarios. The results point to thermal and voltage violations within the Michigan power system that will further

prevent imports. Post-processing the results identifies these additional constraints by highlighting the most critical contingencies and planning criteria violations.

The most significant advantage of the developed visualization method is the ability to analyze immense quantities of data from a variety of scenarios and sensitivity levels quickly, thereby making connections and easily identifying relationships in the data. Understanding more scenarios quickly is essential for planners to understand because the uncertainty surrounding the future of grid development. For example, there are varying renewable integration policy targets, long interconnection queues with uncertainty regarding which projects will proceed to be built, and increased electrification.

KEYWORDS

Power flow constraints, AC Contingency Analysis, Visualization Methods, Heat Maps, TARA, Transfer Capability, MISO.

A INTRODUCTION

The power grid in the United States is undergoing significant changes due to the increased penetration of renewable resources and the retirement of conventional generating facilities such as coal plants. Understanding the effects of these significant change is essential to guaranteeing proper system operation and reliability.

Promptly comprehending the vast tables of outcomes from AC contingency analysis tools is an immense challenge for power system planners. Engineers have struggled with understanding the findings and identifying relevant mitigations because of the enormous volume of data and the difficulty of connecting related outcomes using tabular data. The data presentation limitation was the biggest motivator of the current analysis, developed to present the data clearly and emphasize its connections by employing visualization techniques.

To illustrate the developed approach, the technical capacity of the transmission system in and around the state of Michigan to transfer power from regions identified as having the potential for renewable generation resources to the load-center areas was used. Michigan is particularly interesting for planning purposes because its reserve margins have narrowed, while the pace of transition of Michigan's electric power fleet has significantly increased. The impacts of declining reserve margins and retiring coal plants were evident during high-load emergency conditions in. the Midcontinent Independent System Operator (MISO) study sponsored by the Michigan Agency for Energy (MAE) and the Michigan Public Service Commission (MPSC) in 2019 [1]. To forecast short- and long-term outcomes in Michigan, the study developed models using a variety of assumptions, sensitivities, and scenarios. The models considered known and projected coal plant retirements in Michigan in addition to projections for power demand and new renewable energy plant connections.

With the acceleration of Michigan's generation fleet transition, assumptions made in 2019 to forecast coal and nuclear plants' retirement and new renewable generation plants needed to be updated. Thus, traditional plants already retired in 2022, and the planned retirements to be done by 2025 were considered. In addition, renewable generation projects present in 2023's MISO Generation Interconnection Queue [2], which are expected to be in operation by 2025, were also added to the model developed.

Making connections and finding linkages in the vast amount of data much more rapidly is critical for planning cases like Michigan and other future scenarios with considerable uncertainties. The developed visualization method aims to overcome the previously identified data analysis and presentation problem.

B METHODOLOGY

The software tool TARA [3] was used for the project's AC power flow and contingency analysis. To investigate Michigan's transmission system capacity, 2025 base cases of Summer Peak and Shoulder (with 40% of wind dispatch) from MISO's Transmission Expansion Planning 2020 (MTEP20) [4] were considered. The cases were modified to reflect four conventional plant retirements, including plants that were decommissioned in 2022 and those that are scheduled for decommissioning by 2025. Areas and zones of potential renewable power were identified using the 2023 MISO Generation Interconnection Queue to add new generations to the updated cases. Finally, large scale transmission system projects were taken into account, such as LRTP Tranche 1 (Long Range Transmission Planning: Tranche 1) [5].

B.1 Transfer Capability

The transfer capability analysis was conducted among multiple regions to monitor several interfaces and identify each region's net generation and load. As a result, not only was a single transfer capacity study performed, but also many sensitivities were considered in evaluating the various outcomes.

In the Michigan test case, the system-peak model dispatches more generation outside of Michigan (source region) and less generation inside Michigan’s lower peninsula (sink region). As a result, more energy flows into Michigan, bringing attention to transmission limitations that restrict further imports. The evaluated source regions are the areas that border Michigan electrically: American Electric Power - AEP (PJM), American Transmission Systems, Incorporated - ATSI (PJM), Northern Indiana Public Services - NIPS (MISO), and Ontario (IESO). Figure B-1 shows the transfer capability approach applied to the State of Michigan.

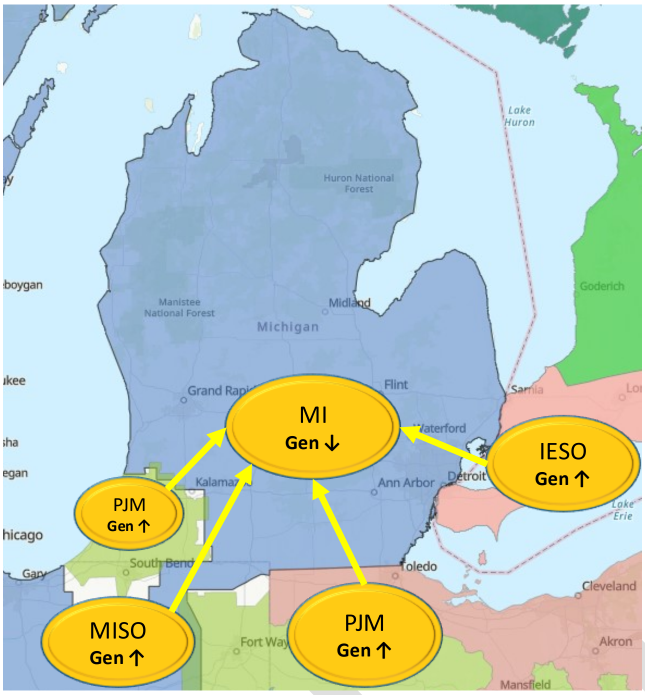

Figure B-1: Michigan's transfer capability interconnection region definition

The transfer capability analysis begins by reducing the generation in the sink region by 500 MW and increasing the generation in the source region by the same amount (combined interfaces). Iteratively, the generation is modified in steps of 500 MW until reaching the maximum transfer level of 9000 MW for the Summer Peak case. Figure B-2 shows the interface flows to Michigan when LRTP Tranche 1 (Long Range Transmission Planning: Tranche 1) is not in operation and Figure B-3 shows the case when LRTP Tranche 1 is operation. Comparing both graphs, it is apparent that the addition of the transmission enforcement increases the transfer capability inside the MISO region, as Michigan can now import more power through this interface. It is also notable that most of the power imported comes from the PJM interface, even though Michigan is inside MISO's territory. Lastly, it is possible to observe how the PARs located at the IESO border dictate the power transfer behaviour at this interface. While PARs introduce complexity at the border interface, this approach is effective if PAR control and generation-to-generation transfers are coordinated. The power transfer capability in Michigan and the impact of LRTP Tranche 1 can be easily and quickly analyzed by the implemented visual tool.

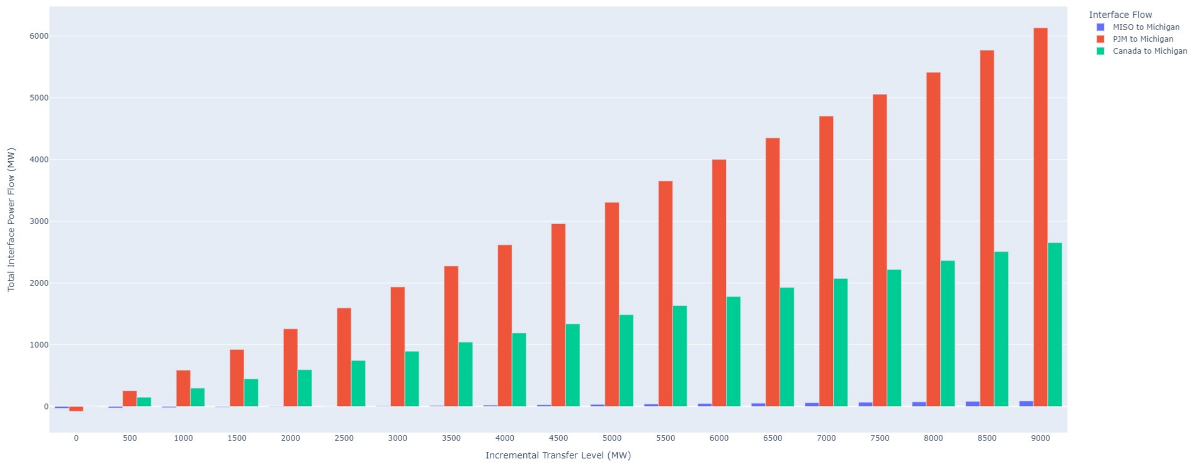

Figure B-2: Michigan maximum transfer capability without LRTP Tranche 1 – Summer Peak Case.

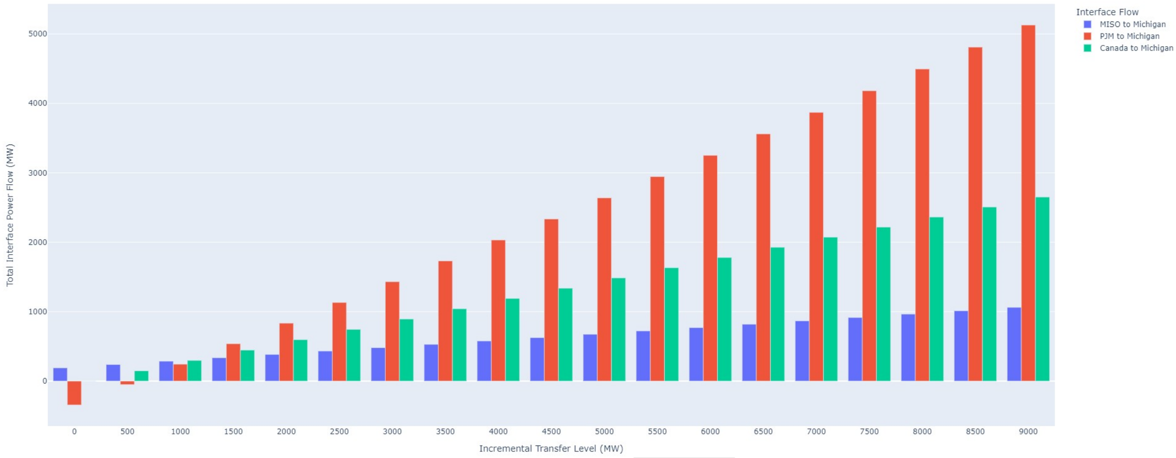

Figure B-3: Michigan transfer capability with LRTP Tranche 1 – Summer Peak Case.

B.2 Contingency Analysis

After the power transfer analysis was completed, the contingency analysis was performed, considering N-1 conditions. The contingencies applied were taken from the MISO MTEP20, but filtered to include only events inside Michigan, resulting in 2715 contingencies. They include P1, P2, P4, and P5 categories, defined by NERC's Transmission System Planning Performance Requirements (TPL-001-5) [6].

The analysis applies the 2715 contingencies to all cases generated in the transfer capability analysis: 19 for Summer Peak without LRTP Tranche 1, and 19 for Summer Peak with LRTP Tranche 1. Investigating almost 40 cases for the buses' voltage levels and lines' thermal limits resulted in over 10,000 combinations of flowgate and dispatch conditions. Analyzing the vast amount of output data in tabular format is challenging and time-consuming, making this approach impractical. To deal with the massive output dataset, it is critical to establish a few important summary metrics and process all flowgates in the same way, resulting in a fast summary metrics comparison and a more straightforward method to identify situations that need to be addressed.

The data output was initially narrowed by filtering the contingency analysis results for the cases that showed violations. Thermal and voltage violations were targeted with specific criteria. For thermal violations, lines or transformers with loading over the rated capacity were selected. For voltage violations, situations where the simulated voltage was outside of 0.95 pu and 1.05 pu were selected. After the violated elements were identified, heat maps were used to define the relation of the element, the contingency that caused the violation, and its severity level. For each scenario, the transfer level cases are plotted side by side to compare the violation severity and how the increase in power imports impacts it. An example of the generated heat maps for thermal and voltage violations are shown in Figure B-4. The contingencies that caused violations are shown on the X axis and the affected elements on the Y axis. The color code on the bar on the right side represents the severity of the violation.

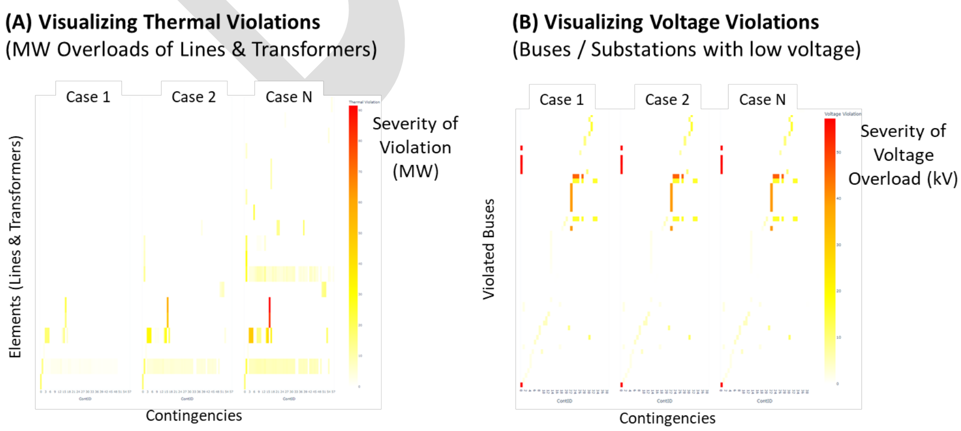

Figure B-4: Developed Violations Heat Maps - (A) Thermal Violations (B) Voltage violations

B.2.1 Lines and Transformers Thermal Violation Analysis

Figure B-5 shows the thermal violations for two high levels of power transfer, 7000 MW and 9000 MW, during the Summer Peak without LRTP Tranche 1 included. It is possible to see that at the highest transfer level, over 300 contingencies cause overloading on more than 34 elements in Michigan. Compared with the 7000 MW transfer level scenario, where much fewer contingencies caused violations, importing 2 GW more takes the system to its thermal limits.

The heat maps also clearly show the impact of transmission system reinforcements. Figure B-6 shows the same transfer levels as Figure B-5 but include LRTP Tranche 1. Compared to Figure B-5, the benefits of LRTP Tranche 1 at the 7000 MW transfer level are not clearly apparent. However, they become most noticeable at the 9000 MW transfer level. The inclusion of Tranche 1 reduces the number of contingencies that cause violations and the number of elements impacted to 244 and 21, respectively. Further, the Tranche 1 reduces the severity of the violations. For example, on the central Michigan area, where the worst violations are concentrated, the overloads were reduced by up to 15%.

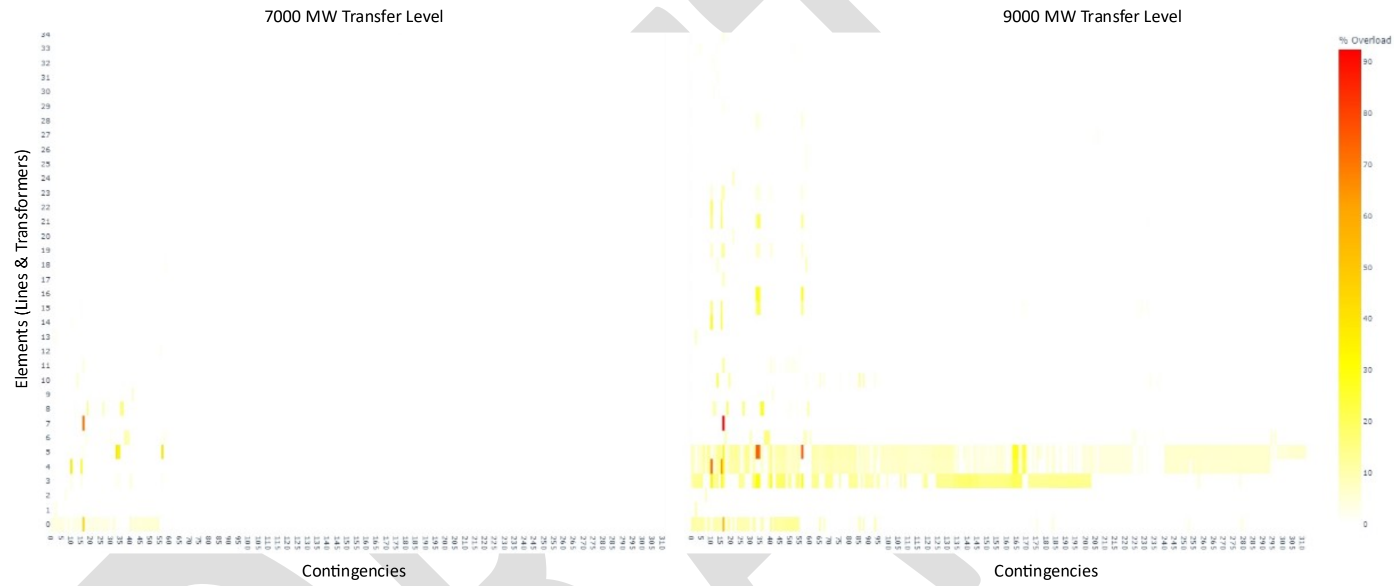

Figure B-5: Thermal violations for Summer Peak case without LRTP Tranche 1

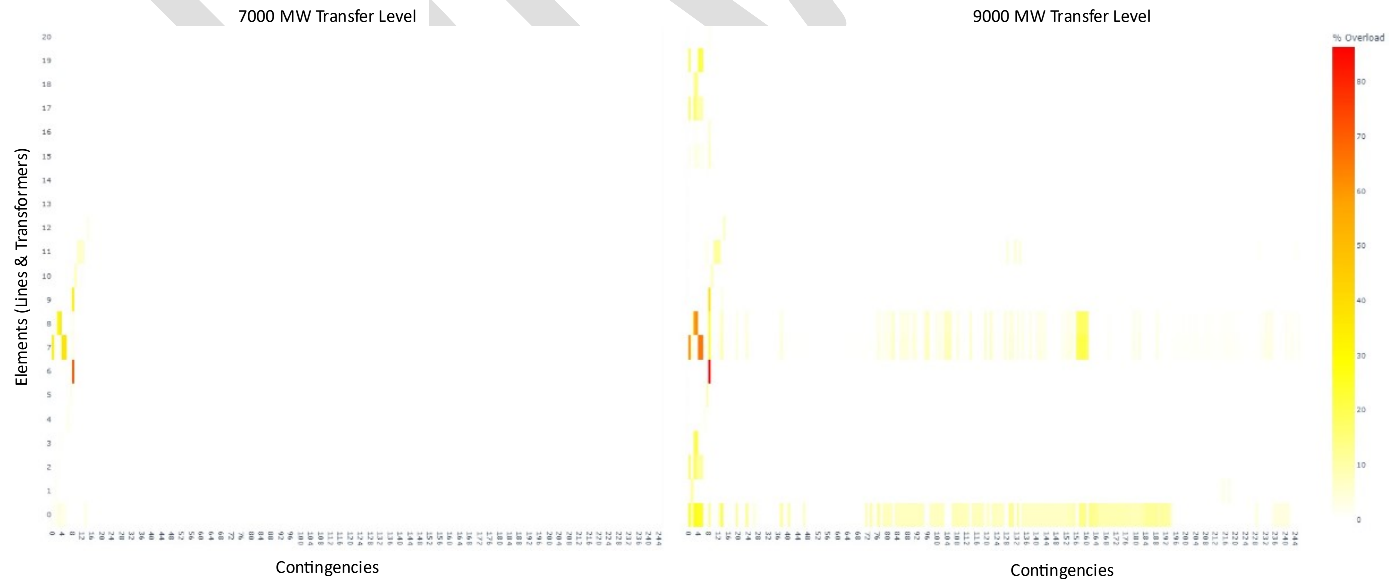

Figure B-6: Thermal violations for Summer Peak case with LRTP Tranche 1

B.2.2 Bus Voltage Violation Analysis

A similar approach was used to analyze voltage violations caused by contingencies as power transfer level to Michigan increases. Increasing transfer levels into Michigan seemed to have limited effect on voltage violations, as observed in Figure B-7 for the summer peak case without LRTP Tranche 1. The worst violations are present even in the lower transfer-level scenarios. There are around 30 more violations in the case with the highest level of imports (9000 MW) compared to the case with lower levels of imports (7000 MW), but the severity of these new voltage violations is minimal. These additional minor violations are mitigated by the construction of LRTP Tranche 1, reducing the buses with voltage violations from more than 100 to 72, as shown in Figure B-8. It is worth noting that the worst violations did not change between cases and were not impacted by the addition of LRTP Tranche 1.

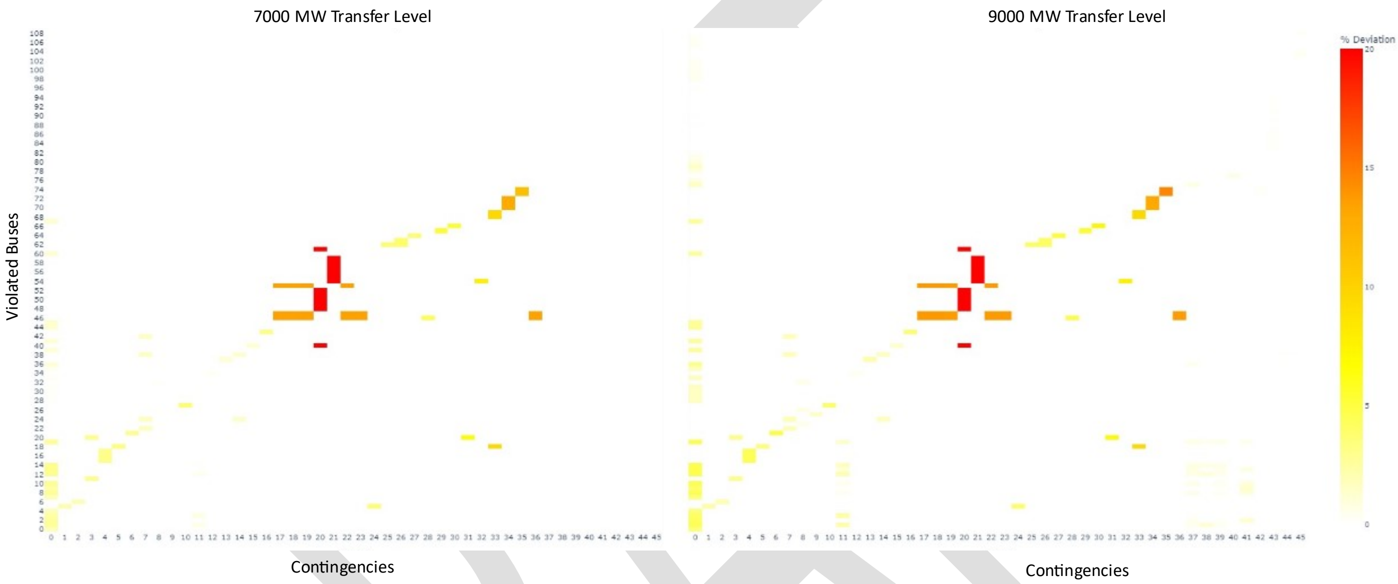

Figure B-7: Voltage violations for Summer Peak case without LRTP Tranche 1

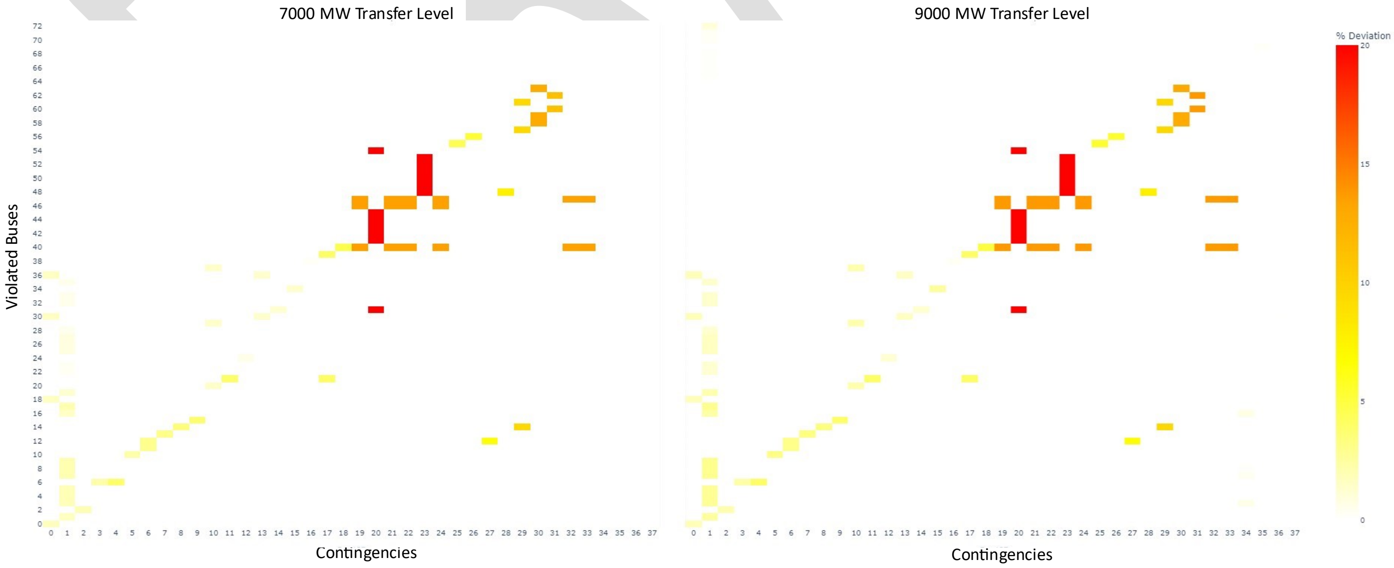

Figure B-8: Voltage violations for Summer Peak case with LRTP Tranche 1

C RESULTS AND CONCLUSIONS

The analysis identified Michigan's import limit capacity and the transmission system's weaknesses while generating extensive data outputs from many cases, scenarios, and sensitivities. Almost 40 power transfer cases were developed, and 2715 contingencies were applied, generating over 10,000 results. If conducted in the usual manner by analyzing tables, this work would be significantly more challenging, and the conclusion would not be straightforward.

The bar graphs allowed the identification of the particulars power transfer capability of each source region. For example, although Michigan is part of MISO, there is only one connection between the state and the rest of the operator's area, which reduces the transfer capability of this interface. Hence, the LRTP Tranche 1 project was shown to be essential in increasing the power transfer to Michigan from MISO's territory. Nonetheless, even with the addition of LRTP Tranche 1, PJM has the most significant transfer capability with Michigan through AEP and ATSI areas. Finally, the transfer with Ontario (IESO) is a particular case since the four phase shifters in the Detroit area dictate the transfer limits.

By applying the heat map approach, the contingency analysis results could be visualized at a system level, comparing cases side-by-side for sensitivities like transmission upgrades or power transfer levels, as performed in this analysis. The impact of thermal violations to the power import level was well identified, and the problem elements were easily targeted. In addition, it was noted that the voltage violations are not highly impacted by increasing the power imports as with lines and transformers. As a conclusion for Michigan's future, the analysis showed how new renewable generation connections are limited by the current transmission system in the state, especially in its central area.

The visualization approach applied enables more efficient analysis of massive amounts of data from a range of cases and sensitivity levels, resulting in faster linkages and identification of relationships among the data. As the future becomes more uncertain due to factors like changing public policy, long interconnection queues where it is unknown which projects will proceed, and rapid load increase due to industry electrification, understanding more scenarios quickly is essential for planning.

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