Power Flow Model Building with SUGAR: A MISO Case Study

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1 Executive Summary

Ulteig Engineers, Inc. (Ulteig) performed a model build exercise on Midcontinent Independent System Operator (MISO) Transmission Expansion Plan (MTEP) models representing an equivalent of a Definitive Planning Phase (DPP) model build process using Pearl Street Technologies' (Pearl Street) Suite of Unified Grid Analyses with Renewables (SUGAR).

MISO and similar organizations develop and maintain interconnection model building processes similar to the DPP which often involve teams of engineers and manual approaches to arrive at numerically stable and solved states for subsequent analysis. The purpose of the exercise was to explore and evaluate an automated approach to model building using SUGAR, with the implementation of MISO's process serving as a basis for comparison, i.e., to evaluate time savings, efficiency, and model quality with and without SUGAR.

Ulteig implemented the DPP model build process programmatically using SUGAR's Python API. The results demonstrate that utilizing SUGAR for MISO's model build process can yield gains in time efficiencies, and its outputs can be used to consistently and reliably create mitigation strategy when necessary. An overview of findings are as follows:

- **SUGAR's performance demonstrated significant time reductions for the queue scenario model building process: a typical three-week process was reduced to a single working session lasting thirty minutes or less.**
- **Models produced using SUGAR are consistent with current practices in terms of model quality based on comparisons of contingency analysis results (i.e., total thermal and/or voltage violation counts) and simulation convergence.**
- **SUGAR can help automate diagnoses of root causes of non-convergence for mitigation.**

2 Motivation

Pearl Street develops software for power grid reliability simulation and optimization. Its SUGAR software has been deployed at ISOs/RTOs, utilities, project development companies, and engineering consulting firms for applications including renewable project siting and grid capacity analysis, auto-identification of low-cost grid upgrades to meet reliability standards, extreme event analysis, creation of long-term planning models, and more. It draws inspiration from the electronic design automation tools that enable the simulation and optimization of billion-node computer chips, leveraging advances in circuit simulation to enable robust analysis of the power grid.

The objective of this Technical and Business Assistance (TABA) supplement project, funded through the National Science Foundation under Grant No.1951083, was to contract an industry-leading, respected third-party engineering consulting firm to highlight the capabilities of SUGAR for renewable energy and storage project interconnection in a detailed case study. The case study will help Pearl Street better communicate SUGAR's value proposition to potential customers (particularly those that perform grid reliability analyses of renewable energy projects), allowing these prospects to understand where SUGAR can help accelerate studies associated with new project interconnections. Having a respected third-party consulting firm conduct and author the study will lend additional credibility to the results.

Pearl Street contracted Ulteig Engineers, Inc. (Ulteig) to develop a case study highlighting applications in renewable energy generation interconnection. Specifically, Ulteig utilized grid models representing the MISO footprint to demonstrate and document the following benefits:

- Automated creation of grid models based on adding and sinking 100+ GW of queued renewable generation projects into existing base MISO Transmission Expansion Plan (MTEP) models
- Localization and quantification of system infeasibilities that require mitigation in the form of new facilities
- Automated sizing and placement of reactive support facilities to prevent voltage collapse

In addition to the system operators or utilities that perform the engineering studies to assess the impacts of new projects on the grid, the benefit of these applications also extend to renewable energy project developers. Each of the model building process components listed above can often be time-consuming, manual, subjective, and non-repeatable due to the limitations of existing power flow software. Siting and sizing of facilities to resolve reliability issues, particularly those that resolve voltage collapse, may rely on the judgment and intuition of experienced engineers. By highlighting SUGAR's ability to automate these applications through its advanced optimization engine, Pearl Street, with the support of Ulteig, aims to garner interest from grid operators, utilities, and developers that could utilize SUGAR to perform these studies with high degrees of efficiency, accuracy, and consistency.

3 Background

3.1 Generation Interconnection

New generation interconnecting to the power grid in North America must go through a process known as Generation Interconnection Procedures. The interconnection process is typically a series of technical studies conducted by the Independent System Operator (ISO), Transmission Owner (TO), and/or electric utilities. The ISO/utility will typically outline their respective process in the Large Generation Interconnection Procedure (LGIP) section of their Business Practice Manual (BPM) along with any relevant supporting information. Interconnection processes are intended to identify potential impacts on the existing bulk electric system and to cost allocate any necessary network upgrades that would enable interconnection of the generation to the grid. The types of studies conducted include, but are not limited to, power flow, short circuit, dynamic stability, deliverability, and sub-synchronous resonance.

Interconnection power flow studies typically have the greatest potential cost impacts on new generation projects. Power flow studies simulate specific grid scenarios to determine if power flows on transmission lines or voltages at nodes/buses meet specific reliability standards. If transmission line flows or bus voltages are not within tolerance due to the interconnection of new generation, network upgrades are assigned to the entity requesting interconnection of the project. These upgrades are intended to ensure reliable grid operation (i.e., within tolerances as defined by reliability standards) once the new generation interconnects. Upgrades proposed due to power flow studies can amount to billions of dollars allocated across a group of entities looking to interconnect new generators. These large costs are often associated with proposed upgrades that include new high voltage AC transmission lines that can be hundreds of miles long. Transmission lines are needed to enable the reliable flow of power from new generation to load centers (e.g., large cities) and to reinforce the voltage stability of large regional power transfers. Most new generation projects seeking interconnection are renewable energy projects, and they are often sited in remote areas far from conventional base load generation (e.g., coal or nuclear), making new transmission lines necessary for these projects to deliver power.

Generation interconnection study processes typically consist of four serially-conducted phases: Feasibility Study, System Impact Study, Facilities Study, and Generation Interconnection Agreement. The Feasibility Study provides an initial cost estimate of any upgrades associated with and assigned to the new generation. The Feasibility Study is relatively low-cost and fast, and the study's cost estimates are understood to be approximate. The System Impact Study (SIS) is typically the core of generation interconnection process. The full suite of analysis completed by the ISO/utility is typically completed during the SIS phase. The SIS can take months to complete and can comprise analyses for a single new interconnecting generator or for a group of generators interconnecting within the same timeframe, often referred to as a queue group, cycle, or cluster. SIS outputs often include a set of network upgrades and cost allocation to each new interconnecting generator. The Facilities Study conducts preliminary design on the network upgrades identified in the SIS to fine tune any assigned cost estimates. Cost estimates determined in the Facilities Study will typically be carried into the final portion of the generation interconnection process, the Generation Interconnection Agreement (GIA). The GIA memorializes all costs associated with the new generator's interconnection into a legal document that commits the new generator to a payment schedule and guarantees a schedule for the interconnection and energization of the new generator on the grid.

Figure 1: MISO Footprint[1]

3.2 Midcontinent Independent System Operator (MISO)

MISO is one of seven ISOs in the United States. Its footprint spans from north to south along the Mississippi River and extends across fifteen US states, as seen in Figure 1. MISO's market generation capacity is approximately 187 GW and has a market historic peak load of approximately 127 GW set on July 20, 2011. The current generation mix in MISO is shown in Figure 2. In-service renewable energy in MISO breaks down to approximately 28 GW of wind and approximately 2.4 GW of solar. The active generation interconnection queue size is approximately 132 GW, compromising approximately 15 GW of wind and approximately 81 GW of solar as of February 15, 2022.

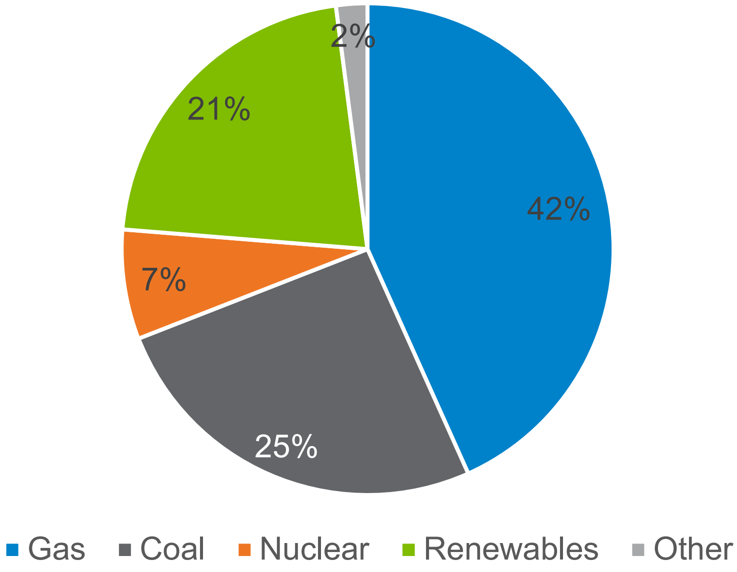

Figure 2: MISO In-Service Generation by Fuel Type[2]

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[1] https://cdn.misoenergy.org/MTEP21 Full Report including Executive Summary611674.pdf
[2] https://www.misoenergy.org/about/media-center/corporate-fact-sheet/

3.3 MISO Generation Interconnection Studies

Generation interconnection in MISO is unique in several ways. MISO was the first ISO to pioneer the three-stage System Impact Study to manage the study of new generators in large groups. MISO is also among the ISOs that face increasing large demand for renewable generation interconnection. The last window for generation interconnection applications in 2021 contained approximately 75 GW spread across 478 different interconnecting generators, accounting for well over half of MISO's active study queue.

MISO uses a contingency analysis-based method for conducting power flow studies for generator interconnection where pre- and post-project contingency analysis results are compared. This comparison is the basis for upgrade cost allocation based on their incremental impact on the models. The dispatch methodology for this method drives the results, because the magnitude and location of the new generation will greatly impact contingency analysis results.

A combination of the need for pre- and post-project cases and the necessity to study several planning scenarios requires MISO to build multiple models throughout the MISO interconnection process.

3.4 SUGAR For Generation Interconnection Model Building

Generally, SUGAR yields time efficiencies in model building processes by translating what is often a manual, time-consuming, and iterative power flow solution approach in other power flow simulation platforms to an automated, programmatic, and repeatable process without loss in solution quality (i.e., violation counts and/or slack bus settings).

While automation is inherently, and necessarily, a part of existing model building processes and practices, limitations of power flow solvers ultimately require intervention by engineers to achieve an end result. For example, a non-convergent solution from another power flow platform typically points to one of two conclusions: 1) A solution exists, but the power flow algorithm struggles to progress toward the solution space, or 2) A solution definitively does not exist. From an initial non-convergent solution provided by other platforms, engineers must process and interpret output files and terminal logs to determine possible root causes and take corresponding action. Typically, they will implement and test a possible fix and re-run the power flow simulation, a subjective process which can occur hundreds of times before either an adequate power flow solution for a given model is found, or engineers determine that the system has no solution as-is. In the case of a non-solution, backbone real or reactive power support (i.e., new transmission lines or VAR compensation) may be necessary to solve the model, which incurs yet another manual, subjective, and repetitious process. SUGAR's power flow solutions provide improvement not only by being better able to more robustly compute solutions where other power flow solvers cannot, it also automates determination of localized real and/or reactive power mismatches at system nodes. This approach places any required reactive backbone support and can more efficiently guide a user towards valid real power mitigations needed to achieve a solution, all of which is configurable in accordance with a user's specified criteria. Further, this process is repeatable subject to any possible changes to input or criteria-based assumptions for a given model, allowing for any number of active interconnection process models and/or queue outcome scenarios to be developed and analyzed.

SUGAR is a suite of tools that, among other steady-state power system analysis applications, increases the efficiency of power flow model build processes. The software utilizes advanced circuit analysis and optimization principles from the computer chip industry to create a robust power flow solver. The software leverages its optimization capabilities to also provide insight into solution infeasibilities, allowing engineers to more efficiently conduct studies that require power flow simulations of the most challenging grid scenarios.

4 Methodology

MISO provided Pearl Street and Ulteig with the MTEP21 models for Summer (SUM) and Fall/Spring Shoulder (SH) for the 2026 planning horizon, which aligns this model build with the Definitive Planning Phase 2021 Cycle (DPP-2021-Cycle). Ulteig utilized its understanding of the MISO generation interconnection process for how to conduct the model build exercise, with confirmation from MISO engineers.

Ulteig first created a list of generators to add to the models. MTEP21 models contain no active queued generation, and they only have generation requests that have executed their GIA by the beginning of the MTEP21 model creation process. Ulteig documented actively queued projects from the public MISO generation interconnection queue by searching for the English point-of-interconnection (POI) names provided in the queue. These English POI names were then mapped to power flow buses and/or lines in the MTEP21 models.

Queue priority of the actively queued projects was broken down into two groups for the purposes of the model build: Prior and Current. The prior queued projects were projects in the DPP-2018-APR, DPP-2019-Cycle, and DPP-2020-Cycle groups. The current queued projects were the DPP-2021-Cycle group. A summary of these priority classifications are shown in Figure 3.

Prior Queue	Current Queue
DPP-2018-APR	DPP-2021-Cycle
DPP-2019-Cycle	
DPP-2020-Cycle	

Figure 3: Model Build Queue Priority

The model build was completed using SUGAR via two different processes. The first followed the conventional MISO process for building models for use within the GI process via automation scripts that utilize SUGAR. This process preserved the dispatch rules currently used in MISO GI studies. The second process utilized SUGAR's Builder module. This process utilized SUGAR's dispatch optimization to create a converged and feasible model.

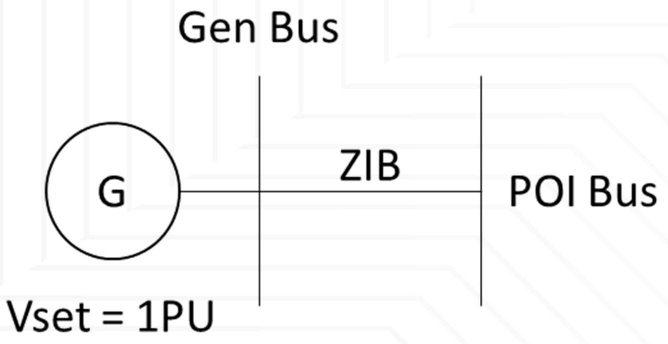

Figure 4: Active Queued Generation Modelling

Actively queued generation was added to the models according to a basic configuration: the active study generator’s voltage setpoint was assumed to be 1.0 p.u. at the local generator bus, and the generator was connected to their POI through a zero-impedance branch. A one-line diagram of the modeling setup for generators added to the models is shown in Figure 4.

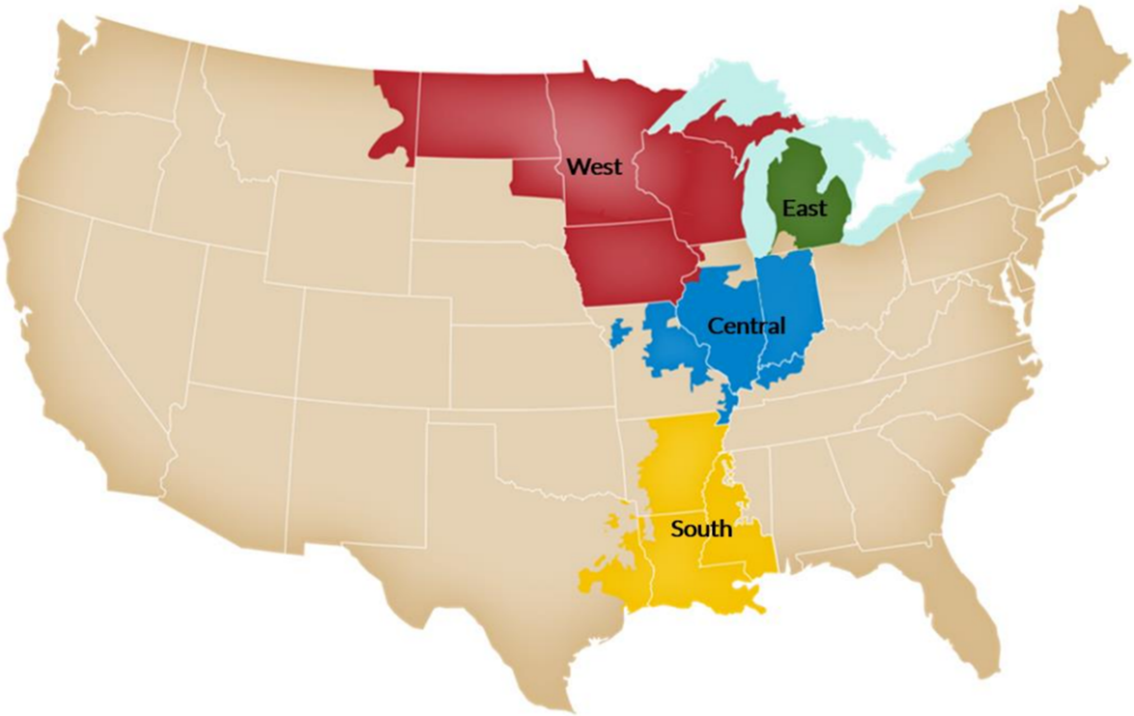

Figure 5: MISO planning regions[3]

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[3] MTEP21 Report: https://cdn.misoenergy.org/MTEP21 Full Report including Executive Summary611674.pdf

4.1 Current MISO Model Build Process using SUGAR

For generation interconnection studies utilizing contingency analysis, two models must be created for each planning scenario. One model represents the existing power grid without the current study's generator impacts (i.e., pre-project) and the second model shows the current study's generator impacts (i.e., post-project). MISO formally refers to the model without the current study generator impacts as the "bench" model; the model with the current study generator impacts is referred to as the "study" model.

The bench model is created from the MTEP models by adding prior queue generation dispatched according to its fuel type. The MISO fuel-based dispatch assumptions are shown in Figure 6. These dispatch changes are compensated by (i.e., "sunk into") the existing MISO footprint by uniformly scaling down existing generation by the amount of new generation added to the model, proportional to the PMAX of the generator. For the purposes of sinking generation, MISO's footprint is split into two regions: MISO Classic (West, East, and Central) and MISO South (see Figure 5). If an active study generator is in MISO Classic, it is sunk to MISO Classic; if an active study generator is in MISO South, it is sunk to MISO South. This is done to preserve the SPP-MISO interface limits.

The study model is created by adding all current queued generation to the bench model and setting the current queue generation to its fuel-type dispatch. The dispatch change caused by the current queue generators is sunk into each generator's respective MISO region, this time including the prior-queued generation.

Fuel Type under Study and Higher Queued	Summer Peak Dispatched as % of Interconnection Service	Shoulder Peak Dispatched as % of Interconnection Service
Combined Cycle	100%	50%
Combustion Turbine	100%	0%
Diesel Engines	100%	0%
Hydro	100%	100%
Nuclear	100%	100%
Storage[4]	100%[5]	+/-100%
Steam - Coal	100%	100%
Oil	100%	0%
Waste Heat	100%	100%
Wind	15.6%[6]	100%
Solar	100%	0%[7]
Hybrid Facility[8] (Any combination of the above fuel types)	Based on above dispatch assumptions of each fuel type with any adjustment based on requested interconnection service[9]	Based on above dispatch assumptions of each fuel type with any adjustment based on requested interconnection service[10]

Figure 6: MISO's BPM-15 Fuel Type Dispatch[11]

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[4] Storage requests need Transmission Service if they will be charging from the Transmission System; GIA does not grant Transmission Service. In order to obtain any type of Transmission Service for charging from the Transmission System, the IC will have to seek service as a Transmission Customer.

[5] For cycles before the DPP 2019 cycle, Storage dispatch in the summer peak case will continue to use the previous value of +/-100%

[6] Dispatch level for wind resources will be aligned with wind capacity credit used in the MTEP summer peak case. It was 15.6% in 2017 MTEP summer peak case. This value is subject to change based on the wind capacity credit which is calculated annually.

[7] For cycles before the DPP 2019 cycle, Solar dispatch in the shoulder case will continue to use the previous value of 50%

[8] A hybrid facility is a Generating Facility that utilizes more than one fuel source to inject power on to the Transmission System. This Generating Facility can be any combination of the fuel types in Table 6-1. For e.g. Solar + Storage, Wind + Storage, Solar + Wind, CC + Solar, Solar + Wind + Storage etc.

[9] See Examples in MISO BPM-015-r23 Appendix E

[10] See Examples in MISO BPM-015-r23 Appendix E

[11] MISO BPM-015-r23 Table 6-1, https://cdn.misoenergy.org/BPM%20015%20-%20Generation%20Interconnection49574.zip

4.2 Incorporation of SUGAR's Builder Module in the Build Process

SUGAR's Builder module automates model building processes by optimally and automatically modifying facilities to create a solved power flow model without manual intervention beyond an initial configuration of solution options.

The process followed by Builder does not follow MISO's generation interconnection redispatch methodology, but its capabilities demonstrate the possibilities of optimized dispatches. SUGAR Builder has appropriate settings to preserve the dispatch methodology used in the current MISO model build process, but Ulteig allowed it greater freedom to explore its capabilities compared to the current process. This study only allowed the generator P/Q setpoints to be controlled to achieve a SUGAR optimized solution.

The process of building bench and study models was effectively the same as outlined in Section 4.1 above, but SUGAR Builder was utilized rather than sinking the active study generators in accordance with MISO's current redispatch methodology. The real power setpoints of active study generators were configured to be non-adjustable in order to preserve the intent of the analysis in capturing the impacts of the new projects on the system.

5 Results

Results in this section were produced on a laptop PC with the specifications shown in Table 1 and utilizing SUGAR Version 1.13.0 in the Python 3.7.9 64-bit environment. SUGAR is a single-threaded process, but several SUGAR threads can be launched in parallel to conduct different scenario model builds in parallel. For example, SUM and SH model builds could be conducted simultaneously.

Table 1: Computer Specifications

CPU	Intel® Core™ i7-8750H
Base Frequency	2.2 GHz
Max Turbo Frequency	4.1 GHz
Cores (Threads)	6 (12)
Memory	32 GB
Storage	512GB NVMe M.2 SSD

The contingency analysis results utilized generic input files. The .mon file was configured to monitor transmission lines within MISO areas. The .con file associated with the MTEP21 models was utilized which included P1, P2, P4, P5, and P7 contingencies in the MISO footprint.

5.1 Data Checking Using SUGAR

It is best practice to run SUGAR's `check_data` API function before any simulations using SUGAR are attempted. This will flag common modeling errors that frequently cause non-convergence in power flow solutions. SUGAR flags potential errors that include, but are not limited to, high transformer and line impedances, high transformer turns ratios, and suspicious/invalid generator QMIN/QMAX limits.

In the case of the MTEP21 SUM and SH models, a three-winding transformer error was discovered. The winding voltage was improperly set for the tertiary winding. Typically, this should not be an issue as the tertiary bus is floating, but this error caused issues with SUGAR's power flow solution algorithm. The error existed in the SUM and SH models. Before correction, this error prevented SUGAR from converging in the SH model after it had been stressed with prior queued generation.

Several other minor errors were identified in the models including two-winding transformers with high impedances, two- and three-winding transformers with suspicious turns ratios, discrete shunts with wide control bands, and QMIN>QMAX for some generators. None of these minor issues caused non-convergence, so to preserve the MTEP21 model state those errors were noted but not directly addressed.

5.2 Current MISO Model Build Process using SUGAR

The current MISO model build process for building the bench and study models for MISO's generation interconnection studies was implemented with scripts using SUGAR's Python API. SUGAR was used throughout the model build process to sink prior-queued and active queue dispatches appropriately as shown in Figure 7. Both the SUM and SH model builds were performed using the scripts, producing solved study models from each off-the-shelf MTEP model. The total simulation runtime to create the two models took less than fifteen minutes total. Output models from SUGAR were validated using multiple power flow platforms.

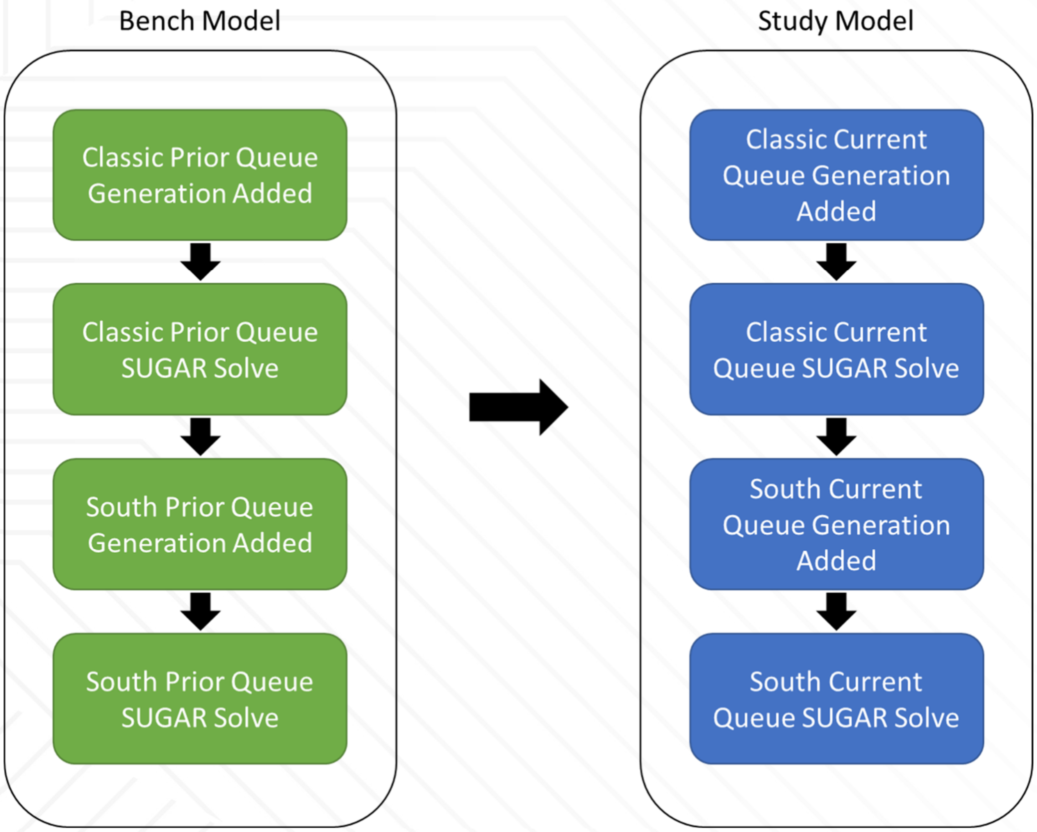

Figure 7: Bench and Study Model Creation with SUGAR

The process of building the models with SUGAR replaces an iterative, and highly manual, process utilizing typical power flow software solvers. It is typical for the MISO model building exercise to encounter limitations of traditional power flow solvers due to the large amount of generation being added to the planning models. A normal model build process consists of attempting to solve the power flow model and running into several solution issues. The most common solve issue is non-convergence of the power flow solution due to bus P/Q mismatch(es) above a tolerance specified in the power flow solver settings. Transmission planners utilize solve setting configurations and manual adjustments to control devices to eventually make changes to the power flow model to get a valid power flow solution. This manual process can take a week for the Bench case and two-plus weeks for the Study case depending on the severity of solve issues. This process may also need to be repeated many times depending on the quantity and extent of changes made to the models throughout the model build process. Further, one engineer making these changes might arrive at a different set of assumptions, adjustments, or results than another, making this process not only manual, but also subjective and reliant on the experience of the engineer(s) developing a given model.

Results using SUGAR show that this multi-week process can be reduced to a single, automated working session of under fifteen minutes for each bench case and study case model build, with the potential for efficiency gains by engineers performing model builds and similar studies. Another advantage of utilizing SUGAR for model building is that the process is easily repeatable, which can alleviate the issues introduced by the manual and subjective tuning of power flow models during model build exercises.

5.3 Incorporation of SUGAR's Builder Module in the Build Process

The Builder module for the MISO model build exercise primarily replaced the power flow solves using SUGAR as outlined in Figure 7 (i.e., the "SUGAR solve" steps). The process with SUGAR Builder also achieved feasible power flow solutions in under fifteen minutes from off-the-shelf MTEP21 models to solved study models. Output models were again validated using multiple power flow platforms.

As described above, SUGAR Builder offers capabilities to automatically place reactive power support devices. However, throughout this model building exercise SUGAR was able to find feasible solutions without the need for additional reactive support devices.

5.4 Model Comparisons of System Violations

SUGAR provided converged and feasible power flow solutions following the current MISO model build process and with SUGAR Builder. However, the solutions produced via these two approaches are not the same. To compare the solutions, aggregate voltage and thermal violations identified in contingency analysis results from the MTEP models were compared against corresponding results in the output bench and study models from the two model build processes (i.e., five total models for each of the SH and SUM scenarios). This section summarizes in tabular format results for the various models, and they are indicated as follows:

MTEP – base MTEP model

Bench – bench model solved via implementation of MISO's model build process in SUGAR

Bench Builder – bench model solved using SUGAR's Builder module

Study –study model solved via implementation of MISO's model build process in SUGAR

Study Builder – bench model solved using SUGAR's Builder module

5.4.1 Bus voltage violation comparison

The first metric compared was base case voltage violations. A base case voltage violation is defined as a bus voltage outside the 0.9-1.1 p.u. range under system intact conditions. Table 2 and Table 3. show comparisons of violations in SH and SUM models, respectively. In general, base case voltage violations increased as more active study generation was added to the power flow models. The trend of base case voltage violations increasing from the MTEP model to the bench model to the study model is expected as new generation is added to the models. Bus voltages become stressed because certain areas may not have adequate voltage support, or the proper device control parameters are not set.

For the SH models, the Builder-based approach produced relatively worse results compared to the implementation of the current MISO model build process in SUGAR for the bench case. However, that result reversed for the study case, where the Builder-based process produced fewer base case voltage violations.

Table 2: Base case voltage violations for SH models

SH MTEP	16
SH Bench	30
SH Bench Builder	38
SH Study	64
SH Study Builder	41

For the SUM models, the current MISO build process implemented in SUGAR and the Builder-based approach produced similar results. The Builder-based approach again performed better in producing fewer base case voltage violations compared to SUGAR utilizing the current MISO model build process for the study models.

Table 3: Base case voltage violations for SUM models

SUM MTEP	19
SUM Bench	39
SUM Bench Builder	40
SUM Study	64
SUM Study Builder	54

5.4.2 Voltage deviation violation comparison

Voltage deviation measures the impact of contingencies (cons) on bus voltages throughout the MISO footprint in the models. Voltage deviation violations are reported for deviations greater than +10% or less than -10%. The voltage deviation results are shown for SH and SUM model builds in Table 4 and Table 5, respectively.

The SH model results do not show a dramatic difference between the SH MTEP model and the SH Bench model. However, the SH Bench Builder model produced fewer voltage deviation violations in both the bench and study models. The relatively high number of voltage deviation violations seen in the SH Study model is to be expected, especially considering the level of new generation added and the lack of tuning of voltage setpoints for newly added generators.

Table 4: Voltage deviation violations for SH models

	Bus/Con Pairs	Distinct Buses	Distinct Cons
SH MTEP	1058	568	238
SH Bench	1007	552	185
SH Bench Builder	880	512	189
SH Study	6485	328	518
SH Study Builder	869	489	158

The results for the SUM model saw a general reduction in bus/con pairs in the bench and study models compared to the MTEP model. This indicates that the large amount of generation added to the models likely improves low voltage conditions. The standout result from the SUM scenarios is the SUM Study Builder model, where the number of bus/con pairs that had a voltage deviation violation was greatly reduced. SUGAR’s Builder module does not directly optimize for bus voltage deviation, and this is likely an effect from Builder conditioning bus voltages such that contingencies have less overall impact on the bus voltage deviation.

Table 5: Voltage deviation violations for SUM models

	Bus/Con Pairs	Distinct Buses	Distinct Cons
SUM MTEP	2413	1187	378
SUM Bench	1963	1049	317
SUM Bench Builder	1781	1029	294
SUM Study	1956	1113	328
SUM Study Builder	58	52	9

5.4.3 Line overload violation comparison

Monitored elements overloaded under contingency conditions are a significant metric for generation interconnection studies, because they can dictate costly network upgrades. For the purposes of this study, an overload is characterized as the exceedance of a thermal rating, RateB (Rate2), on a specific monitored element (e.g., a transmission line or transformer) during a contingency scenario. Overloads of monitored elements can occur in the base case, and these overloads are to be expected as power injections in the grid shift from locations near existing generators with built-out transmission infrastructure to locations near new generation interconnections which may not have adequate transmission reinforcement.

Thermal overloads are commonly paired according to distinct monitored elements (mons) and contingencies (cons). This provides a perspective if a specific monitored element is overloaded in several contingencies or vice versa (i.e., a “mon/con pair”). Summaries of overloads for the SH and SUM models are given in Table 6 and Table 7, respectively.

For the SH models, the SH Bench and SH Study models have a relatively low number of overloads compared to the SH Bench Builder and SH Study Builder models. This likely has to do with the optimization that SUGAR Builder is performing to achieve feasible, converged solutions.

Table 6: Mon/con overloads for SH models

	Mon/Con Pairs	Distinct Mons	Distinct Cons
SH MTEP	2882	414	942
SH Bench	4268	456	1315
SH Bench Builder	4479	556	1912
SH Study	3673	372	1143
SH Study Builder	7053	718	2745

For the SUM models, the SUM Bench Builder and SUM Study Builder models show improvement compared to the SUM Bench and SUM Study models. Chiefly, the SUM Study Builder model shows dramatic improvement in reducing the number of mon/con pairs which aligns with the other metrics for the SUM models.

Table 7: Mon/con overloads for SUM models

	Mon/Con Pairs	Discrete Mons	Discrete Cons
SUM MTEP	1627	560	941
SUM Bench	5330	922	2364
SUM Bench Builder	6829	945	2295
SUM Study	10865	1310	3624
SUM Study Builder	520	193	76

5.5 Model comparisons of non-converged contingencies

Non-converged contingencies are often a function of voltage collapse during a contingency and is a sign of stress in the model. Non-converged contingencies in MISO's standard power flow analysis software are flagged when the DC loading is overloaded, but no AC loading exists. Non-converged contingencies can be problematic because their mitigation is not always straightforward. Sometimes they can be mitigated through voltage support devices, or they may need to be mitigated by new transmission lines. There are often varying objectives and trade-offs associated with pursuing particular mitigation strategies (e.g., simply solving a power flow model versus considerations of cost).

When a contingency does not converge, SUGAR provides useful information to help the engineer address non-convergence issues. First, SUGAR's solver robustness may converge to a solution that another software platform could not find. The SUGAR solution can then be written out and confirmed in the power flow solver of choice. Second, in instances where a solution truly does not exist due to legitimate collapse conditions, SUGAR computes the amount of real and/or reactive power infeasibility at the bus level, as shown in Figure 8. This bus-level infeasibility computation helps transmission planners easily discern root causes of the non-convergence and produce better-informed mitigation strategies to resolve the issue.

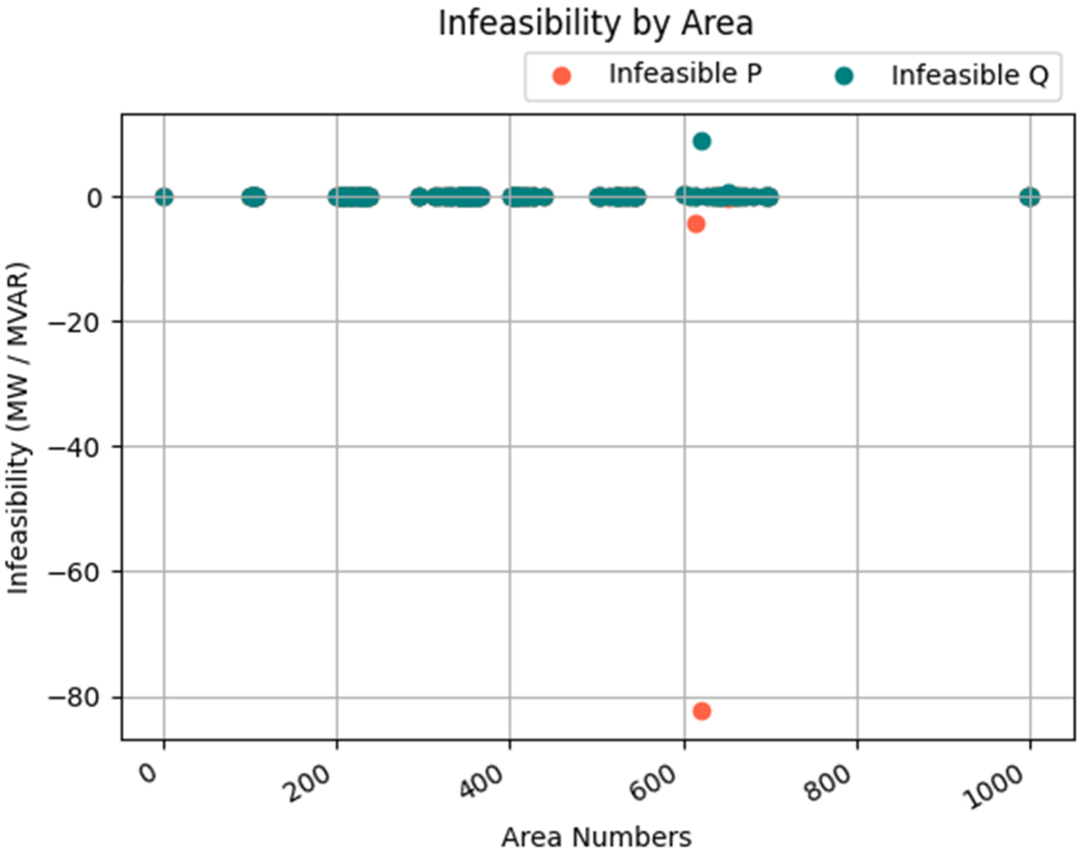

Figure 8: Real power (P) and reactive power (Q) infeasibility by area.

The negative P infeasibility indicates areas with an excess of real power under contingency conditions.

The number of non-converged contingencies for the SH and SUM models are shown in Table 8 and Table 9, respectively, along with the metrics indicating SUGAR's success in finding either a converged solution ("Convergence") and/or a feasible solution ("Feasibility") for the non-converged contingencies discovered throughout the models. Stated another way, if an identified non-converged contingency converges to a feasible solution in SUGAR, the result could be written out and solved in another power flow tool; if the result converges but is infeasible, SUGAR would return bus-level real and/or reactive power infeasibility data to the user.

For the SH models, the SH Study model had the least number of non-converged contingencies. All of the non-converged contingences were able to converge to an infeasible solution in SUGAR, but none of the converged solutions were feasible.

Table 8: Non-converged contingencies for SH models

	Cons	SUGAR Convergence (Cons)	SUGAR Feasibility (Cons)
SH MTEP	4	4/4	0/4
SH Bench	16	16/16	0/16
SH Bench Builder	16	16/16	0/16
SH Study	7	7/7	0/7
SH Study Builder	22	22/22	0/22

For the SUM models, the SUM Study Builder model had no non-converged contingencies. This is likely a continued effect of the solution state of the SUM Study Builder case being relatively robust through examination of these metrics. All of the non-converged contingences were able to converge to a solution in SUGAR, and SUGAR found feasible solutions for a handful of the non-converged contingencies. SUGAR's feasible solutions were validated using other power flow platforms.

Table 9: Non-converged contingencies for SUM models

	Cons	SUGAR Convergence (Cons)	SUGAR Feasibility (Cons)
SUM MTEP	6	6/6	1/6
SUM Bench	16	16/16	5/16
SUM Bench Builder	10	10/10	1/10
SUM Study	31	31/31	0/31
SUM Study Builder	0	0/0	0/0

6 Conclusions and Next Steps

SUGAR integrated into the current MISO model build process produced time savings compared to the process described by current MISO engineers. The process could be reduced to a discrete working session as compared to a multi-day process of manual changes to the model. SUGAR Builder module, although it does not follow MISO generation interconnection redispatch principles, produced model solutions that had improved reliability metrics when compared to the current MISO model build process using SUGAR. Finally, SUGAR was able to find converged solutions for all non-converged solutions from the contingency analysis of the models and found feasible solutions for several of the originally non-converged contingencies.

The findings of this case study can be extrapolated in several ways into new areas. One such area would be to compare the models built to the actual MISO generation interconnection models for the DPP-2021-Cycle. This would provide definitive results with respect to the quality of model build utilizing SUGAR in the current MISO model build process and SUGAR Builder. Another area would be to further explore the infeasible non-converged contingencies to determine if SUGAR Builder is able to provide adequate mitigation to get feasible power flow solutions. Finally, another area to explore would be the optimization of the Vset of active study generators. Adding so much new generation to a power flow model could change the voltage landscape of the model. Typically, the modification of Vset for existing generators is not considered, but the Vset of active study generators is often adjusted to fit into the local voltage topology of the new generator. SUGAR builder does allow for the optimization of Vset and could provide more conditioned power flow solutions.