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Beyond the Snapshot: A Case for Multi-Interval Security Constrained Optimal Power Flow

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Contents

Executive Summary

The Electric Reliability Council of Texas (ERCOT) is advancing its Security-Constrained Optimal Power Flow (SCOPF) capabilities by developing a Multi-Time Security-Constrained Optimal Power Flow (MTSCOPF) solution. This enhancement aims to optimize system operations over multiple hours while addressing thermal, voltage, and stability limits more effectively. Unlike the existing SCOPF, which assesses system constraints at a single point in time, the MTSCOPF will incorporate temporal constraints to improve decision-making and reduce unnecessary control movements.

Key development considerations include optimizing MW and MVAR controls across multiple hours, enhancing Energy Storage Resource (ESRs) and demand forecasting, and ensuring that control actions do not negatively impact stability limits. The MTSCOPF also introduces essential temporal constraints, such as generation ramping limits, State-of-Charge (SOC) constraints for batteries, and restrictions on voltage and reactive power adjustments.

To support effective decision-making, the MTSCOPF will feature a user-friendly interface that summarizes violations, suggested control actions, and detailed analytical views. Performance requirements prioritize robustness, accuracy, and computational efficiency, ensuring that solutions respect operational constraints and align with real-time decision-making.

ERCOT is also exploring advancements in parallel processing and machine learning to enhance computational performance. By leveraging data-driven techniques, ERCOT aims to shift computational load from real-time operations to offline training, reducing solution times while maintaining accuracy. Collaborative research with external institutions is being pursued to explore these emerging technologies.

In parallel, ERCOT is actively evaluating vendor and industry developments to ensure the best practices in MTSCOPF implementation. As of February 2025, ERCOT is enhancing its SCOPF tool to enable both periodic, short-term, multi-hour studies (e.g., HR+1 to HR+4) and scheduled day-ahead analyses. These improvements will provide operators a more comprehensive view of system conditions and enhance grid reliability and operational efficiency.

1. Introduction

Future grid conditions are forecasted using AC power flow cases studied in advance to help system operators better prepare for maintaining reliable operations in anticipated future hours. These AC power flow cases must be solved and "secured" by ensuring that all System Operating Limit (SOL) exceedances are mitigated, with none remaining. SOLs include thermal, voltage, stability, and other interface limits, and they must be secured in both pre-contingency states (initial conditions) and post-contingency states (evaluating facility loss scenarios).

Using a single application or process to secure all SOLs is both the most efficient and the most complex solution. This approach introduces non-linear elements, requiring a robust engine capable of producing timely, consistently converged solutions.

SCOPF extends beyond solving and securing an AC power flow case by optimizing the solution to meet a single or combined objective function. Objectives may include minimizing costs, reducing control movements (i.e., actions taken to mitigate SOL exceedances), or optimizing real and reactive power losses while maintaining necessary reserves (e.g., ancillary service or reactive reserves). SCOPF ensures system reliability under both normal and contingency conditions, safeguarding against failures such as generator or transmission line outages. As a non-linear, non-convex, large-scale optimization problem with both continuous and discrete variables, SCOPF presents computational challenges. However, despite its complexity, single-interval SCOPF engines are widely available in power system study applications today.

The MTSCOPF tool is needed to address these emerging challenges. MTSCOPF can optimize reactive power controls, minimize control movements over multiple hours, maintain voltage levels within acceptable limits, and resolve pre- and post-contingency voltage violations without relying on DC approximations that could compromise solution quality.

This white paper aims to outline the approach and key capabilities required for assessing multi-interval AC power flow cases that are security-constrained and optimized to robustly address key objective functions.

1.1 Differences Between Unit Commitment and Optimal Power Flow

Day-Ahead Reliability Unit Commitment (DRUC) and Hourly Reliability Unit Commitment (HRUC) are two robust, multi-interval power system analysis tools used within ERCOT, both functioning as forms of Security-Constrained Unit Commitment (SCUC). This white paper focuses on developing a new tool: MTSCOPF.

While both SCUC and MTSCOPF ensure system security under contingencies, they serve different purposes and handle time and commitment decisions differently. SCUC determines which generation units should be committed (turned on or off) over a specified time horizon, such as a day or week. Its primary objective is to ensure adequate generation capacity to meet forecasted demand while considering unit start-up, shutdown, and minimum on/off times. MTSCOPF, on the other hand, optimizes the dispatch levels (output) of already committed generation units over multiple time points, without making commitment (on/off) decisions. "Table 1: SCUC vs MTSCOPF" on the next page summarizes the key differences between SCUC and MTSCOPF [1]:

Aspect	SCUC	MTSCOPF
Objective	Decide which units to commit (on/off) and schedule them over a longer period	Optimize power dispatch of already committed units over multiple time points
Commitment Decision	Determines on/off status of units (binary decision)	No commitment decision for generation resources; dispatch only
Time Horizon	Longer-term (day-ahead, week-ahead) with discrete intervals	Usually shorter-term across multiple intervals with committed units
Security Constraints	Ensures system readiness for contingencies over the entire scheduling horizon	Maintains optimal and secure flows under contingencies at each time point

Aspect	SCUC	MTSCOPF
Optimization Variables	Binary (on/off) and continuous (power output) for units	Continuous (MW and MVAR dispatch, voltage setpoints) for generation and discrete (transformer tap positions, shunt device switching, phase shifter angles) for network controls

Table 1: SCUC vs MTSCOPF

1.2 Differences Between Linear and Non-Linear Programming Solvers

SCUC and SCOPF problems have been studied extensively in the literature. Mathematically, they are both a nonconvex, large-scale, mixed-integer optimization problem with a large number of binary and continuous variables as well as a series of prevalent equality and inequality constraints [2, 3]. Solvers for them can be categorized as Linear Programming (LP) and Non-Linear Programming (non-LP) approaches, each with distinct advantages and disadvantages.

"Table 2: LP Solver vs Non-LP Solver" on the next page summarizes the pros and cons of using LP and non-LP solvers for solving the SCUC/SCOPF problem in power systems [1]:

Criteria	LP Solver	Non-LP Solver
Computational Efficiency	Generally faster due to lower complexity in solving linear equations, suitable for large-scale and real-time applications	Slower due to iterative solving of nonlinear equations, which can be a drawback for real-time applications
Solution Accuracy	Often requires linear approximations (e.g., DC approximations), which may reduce accuracy by not fully capturing nonlinearities	Provides higher accuracy by modeling the nonlinear characteristics of power systems directly
Constraint Handling	Limited in handling nonlinear constraints, such as reactive power or voltage constraints, requiring simplifications	Capable of accurately modeling complex, nonlinear constraints without approximations
Flexibility with Objectives	Limited to linear objectives, making it challenging to incorporate complex objectives	Allows for a wider range of objectives, including nonlinear ones like emissions reduction and stability
Implementation Complexity	Easier to implement and maintain due to well-developed,	More complex setup, with a need for tuning to avoid numerical instabilities,

Criteria	LP Solver	Non-LP Solver
	stable algorithms (e.g., simplex, interior-point methods)	but offers more flexibility in problem modeling
Solution Robustness	Provides deterministic solutions, which are reliable and predictable, though approximations may lead to infeasible or suboptimal solutions	Solutions may converge to local rather than global optima, especially in non-convex problems, making robustness dependent on initial conditions and solver settings
Suitability for Large Systems	Highly suitable for large systems due to lower computational cost but may sacrifice some accuracy	Less suitable for very large systems due to higher computational cost, though more accurate in capturing system behavior

Table 2: LP Solver vs Non-LP Solver

2. The Challenge for ERCOT

The rapid transformation of the ERCOT grid, including an accelerated change in the resource mix and a high penetration of renewables, is creating the need to assess system conditions at multiple stressed time points throughout the day, beyond just the peak demand hour. This elevates the need for more efficient tools to perform look-ahead studies across multiple hours to address reliability challenges.

ERCOT conducts various studies across the operations time horizon (real-time up to one year in advance, as shown in Figure 1). These studies use a consistent approach to evaluate pre-contingency and post-contingency flows and voltages against facility ratings, system voltage limits, and stability limits to identify potential System Operating Limit (SOL) exceedances. Stability limits are determined either during the study or from previous studies that represent the system conditions for the operational study. These studies are grouped by time frame, as shown in " Figure 1: ERCOT Operating and Planning Study Time Frame" below below.

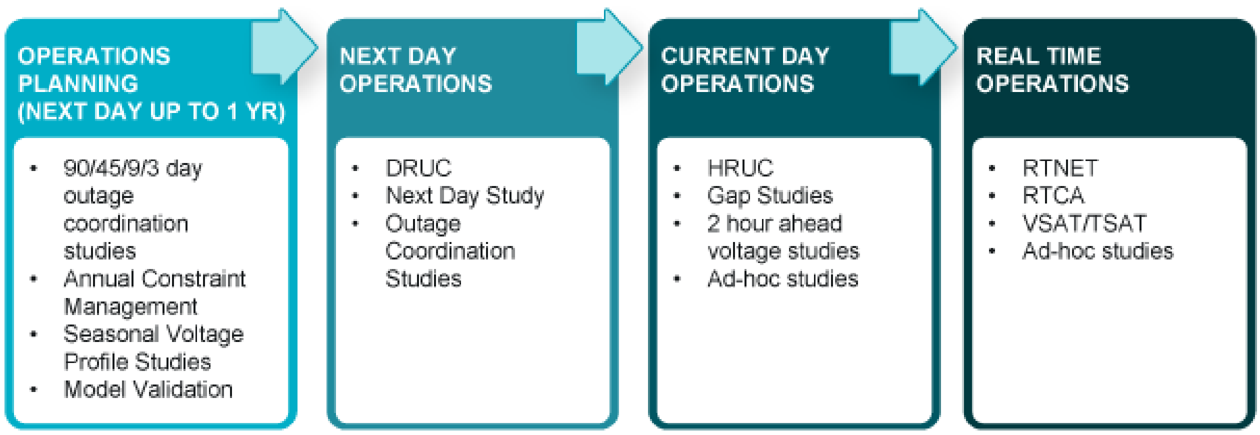

Figure 1: ERCOT Operating and Planning Study Time Frame

An MTSCOPF solution is needed to co-optimize solutions for all SOL exceedances (thermal, voltage, and stability) while respecting known temporal constraints across each of the studies throughout the operations time horizon. This approach would enable screening of future hours to identify the necessary mitigation plans for SOL exceedances that may emerge in real time.

Currently, ERCOT's DRUC (Day-Ahead Reliability Unit Commitment) and HRUC (Hourly Reliability Unit Commitment) applications are limited to evaluating only the next 24-32 hours. These applications focus on MW optimization using a DC solver, which, although robust for short-term solutions, has the following limitations.

- **Linearization Assumptions**: The DC approximation assumes linear relationships, neglecting voltage magnitudes and phase angles. While effective for small disturbances, this assumption can miss potential issues during significant events.
- **Losses Ignored**: Line losses are generally ignored, which may result in suboptimal dispatch and infeasible solutions in real-world systems.
- **Inaccurate Voltage Predictions**: By focusing on power flows without considering voltages, the DC solver may fail to predict over- or under-voltage conditions that can occur under certain operating scenarios.

Additional follow-up studies are required to assess voltage security using the EMS network study application via AC analysis and in-house developed SCOPF for a single time point. This point is typically chosen to represent the most critical time, such as a peak demand hour. However, as the analysis below demonstrates, the system may experience more than one critical hour each day, and the most critical time points can vary monthly (and even daily). Multiple variables, such as Intermittent Renewable Resource (IRR) dispatch variability, outages, and price-sensitive loads, can create SOL exceedances for any future hour. The visual below shows a heatmap of the most critical hours (i.e., those with the most SOL exceedances observed in real time over the past 24 months), highlighting this variability.

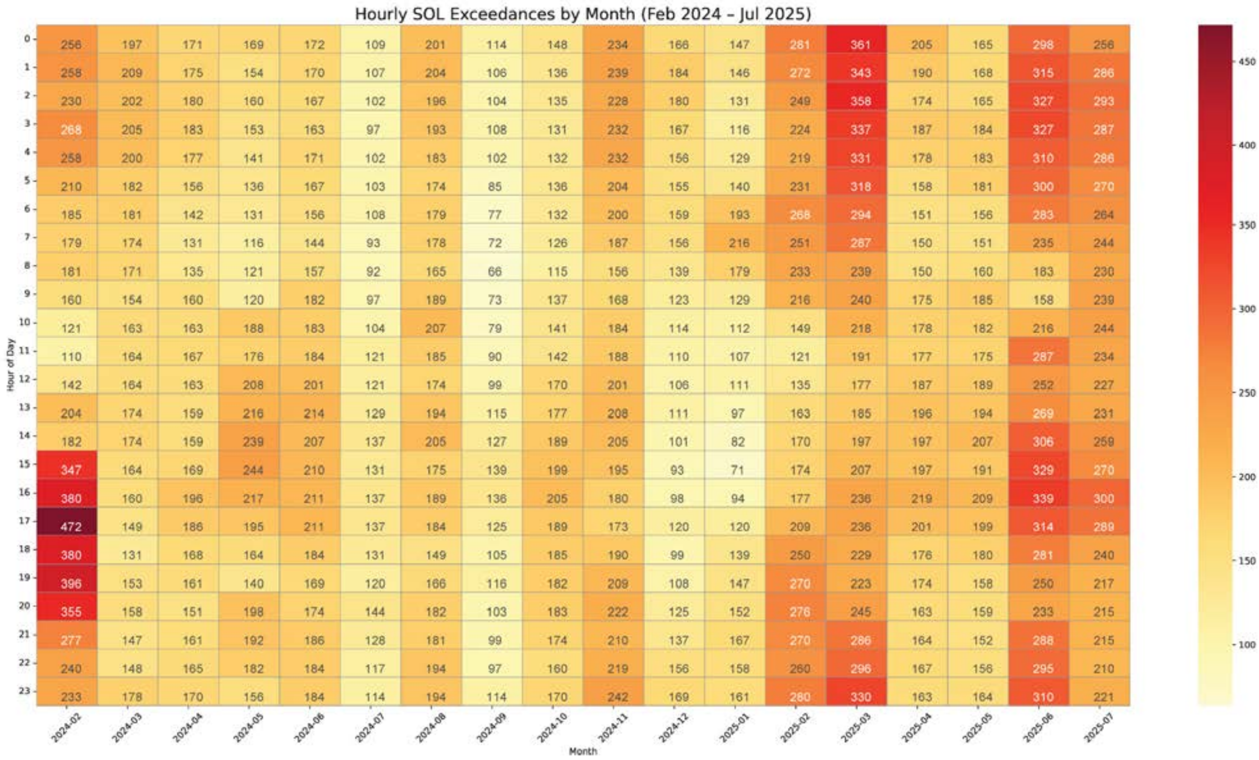

Figure 2: Historical critical time points based on number of SOL exceedances

As the reliability coordinator and transmission operator, ERCOT is required to perform real-time assessments and monitoring to identify and mitigate SOL exceedances. "Figure 2: Historical critical time points based on number of SOL exceedances" above underscores the importance of having the capability to conduct system security analyses for potential stressed conditions and develop mitigation plans more efficiently.

3. ERCOT SCOPF

There are two types of control actions considered in SCOPF: preventive control and corrective control. Preventive control is implemented to avoid undesirable operating conditions in the event of a contingency. Corrective control is an action taken to transition from an emergency state to an alert state, or from an emergency state to a normal state [3]. In current ERCOT in-house developed SCOPF, only preventive controls are considered.

3.1 Formulation and Solution Process

ERCOT's SCOPF [4] adopts a linear programming (LP)-based approach, which is advantageous when incorporating additional security constraints. The mathematical properties of LP problems are well understood, making them easier to analyze and solve. Moreover, LP problems can be solved efficiently using widely used commercial LP solvers. This efficiency is particularly valuable in SCOPF, where numerous contingency scenarios must be evaluated.

ERCOT SCOPF uses an iterative approach to address single-hour thermal and voltage problems, which are tackled in two stages. The first stage involves running non-linear power flow and contingency analysis to determine the network state and identify violations. In the second stage, two linear optimization problems are solved iteratively with the objective of: 1) minimizing total generation cost while resolving thermal transmission constraints, and 2) minimizing the movement of switching devices while resolving voltage violations. Both thermal and voltage violations, along with their corresponding sensitivities, are computed in the first stage, allowing the Mixed-Integer Linear Programming (MILP) problems in the second stage to be formulated sequentially and solved by LP solvers.

ERCOT operations support conducts look-ahead studies that include Power Flow (PF), Contingency Analysis (CA), Voltage Stability Analysis (VSAT), and Transient Stability Analysis (TSAT). These studies initialize the network topology using an Operational Planning (OPA) case model, outage information from the Outage Scheduler (OS), generation plans from Reliability Unit Commitment (RUC) or Current Operating Plan (COP), and real-time load schedules. This planning case serves as a structured baseline, incorporating outage schedules, generation plans, and load forecasts to provide a realistic snapshot of system conditions.

Once initialized, CA is performed to identify MVA (branch limit) and voltage limit violations, helping ensure system reliability and proactive mitigation of potential operational risks [5].

The ERCOT SCOPF is enhanced by adding two tasks – MWSCOPF and MVARSCOPF – to the existing look-ahead studies. MWSCOPF addresses thermal violation issues, while MVARSCOPF handles voltage violations.

"Figure 3: SCOPF Engine " below illustrates how the SCOPF engine determines the control actions (either implemented or suggested) to resolve MVA violations. These actions are based on the objective function, Generic Transmission Limits (GTL), and voltage constraints, serving as preventive measures in the base case to align the OPA with the RUC solution from ERCOT Market Management System.

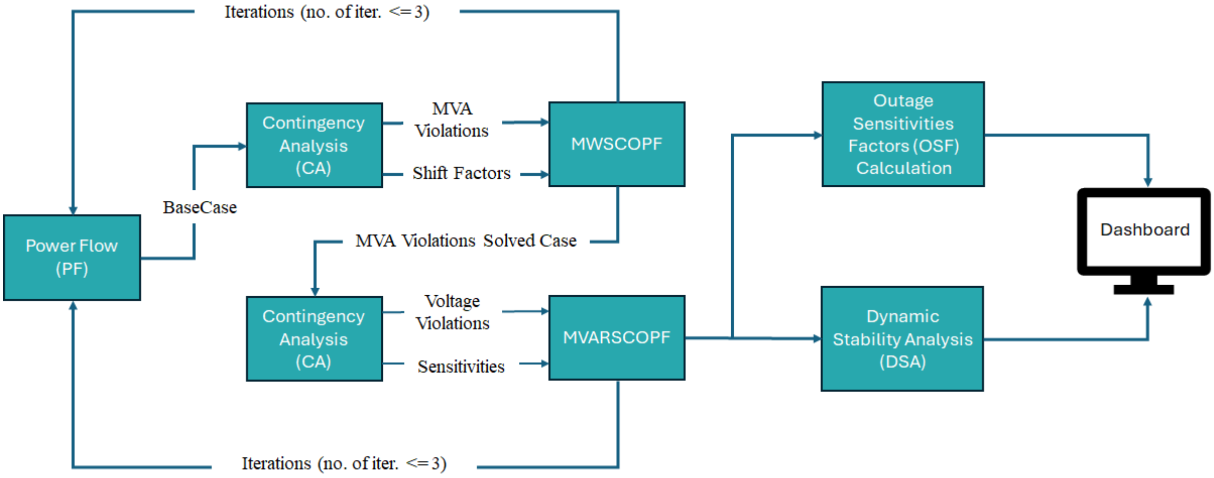

Figure 3: SCOPF Engine

The SCOPF process uses the following input data as indicated in "Figure 4: SCOPF Input/Output" on the next page.

- RUC Output - RUC commitment status to initialize unit status to ON or OFF
- COP Data - Wind and Solar forecast fed through COP
- Outages
- DC Tie Schedules
- Load Forecast

- Dynamic Ratings/Weather Forecast
- Resource Offer Curves

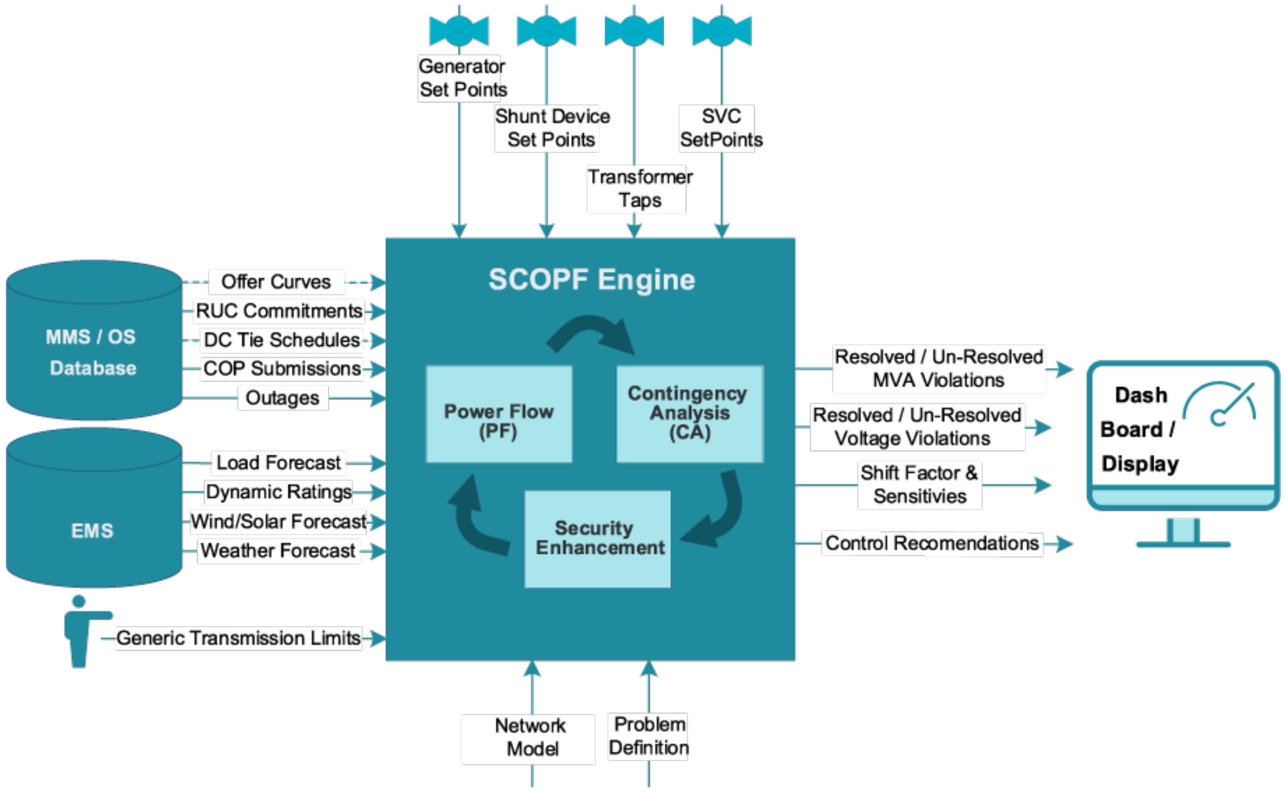

Figure 4: SCOPF Input/Output

The following are the steps taken by the SCOPF solution engine:

1. Initialize SCOPF base case from power flow available with required input data.
2. Perform contingency analysis.
3. Solve and apply recommendations to resolve MVA violations iteratively (maximum of three iterations allowed). Prepares base case for the next step.
4. Solve and apply recommendations to resolve voltage violations iteratively (maximum of three iterations allowed).
5. Optionally perform dynamic stability analysis to see if user input GTLs validity.
6. Optionally calculate Outages Sensitivities Factors (OSF) such that users can manually implement recommendations as potential solution for unsolved MVA violations.

A MW linear optimization problem is formulated to solve the thermal violations, while a MVAR linear optimization problem is formulated to solve the voltage violations. The following are the formulations of two linear optimization problems used in ERCOT SCOPF.

A. MW Formulation

The following is the MW optimization problem.

$$\text{Min}(\sum_{i=1}^{N}(\mathbf{P}_i * \mathbf{W}_i) + \sum_{k=1}^{K}\mathbf{X}_k * \mathbf{W}_k)$$

Where:

$\boldsymbol{i}$:	index of units
$\mathbf{N}$:	number of units
$\mathbf{P}_i$:	output MW from unit *i*
$\mathbf{W}_i$:	energy cost from energy offer curve
$\mathbf{k}$:	index of thermal constraints
$\mathbf{K}$:	number of thermal constraints
$\mathbf{X}_k$:	relax of thermal constraints
$\mathbf{W}_k$:	Penalty of relax of thermal constraints

The first term in the objective function minimizes the generation cost, and the second term minimizes the violations.

Subject to:

1. **Thermal Violation Constraints (from both base case and contingencies)**

$$\sum_{i=1}^{N}\mathbf{S}_i^k * \mathbf{P}_i - \mathbf{x}_{\mathrm{Hi},k} \leq \mathbf{P}_k^{max}$$

Where:

$\mathbf{N}$:	number of units that have significant sensitivities to constraint *k*

$\mathbf{S}_i^k$:	sensitivity of unit i to transmission constraint *k*
$\mathbf{P}_i$:	output MW from unit *i*
$\mathbf{x}_{\mathbf{Hi},k}$:	slack variable for limit violation for transmission constraint *k*
$\mathbf{P}_k^{max}$:	thermal limit for transmission line *k*

2. **Power Balance Constraint**

$$\sum_i^N \mathbf{P}_i - \sum_i^N \mathbf{P}_i^0 = 0$$

Where:

$\mathbf{P}_i$:	MW output for unit *i*
$\mathbf{P}_i^0$:	MW output for unit i before SCOPF

3. **Unit MW limits.**

$$\mathbf{P}_{min\_i} \leq \mathbf{P}_i \leq \mathbf{P}_{max_i}$$

Where:

$\mathbf{P}_i$:	MW output for unit *i*
$\mathbf{P}_{min\_i}$:	minimal MW output for unit *i*
$\mathbf{P}_{max\_i}$	maximum MW output for unit *i*

B. MVAR Formulation

The following is the MVAR optimization problem.

Min($\sum_{i=1}^{\mathbf{M}} \mathbf{C}_i * \mathbf{W}_i + \sum_{k=1}^{\mathbf{K}} \mathbf{X}_k * \mathbf{W}_k$)

Where:

$\boldsymbol{i}$:	index of controllable reactive devices
$\mathbf{M}$:	number of controllable reactive devices

$\mathbf{C}_i$:	status of controllable reactive devices
$\mathbf{W}_i$:	cost of changes made to controllable reactive devices
$\mathbf{k}$:	index of voltage violations
$\mathbf{K}$:	number of voltage violations
$\mathbf{X}_k$:	relax of reactive power constraints
$\mathbf{W}_k$:	penalty of relax of reactive power constraints

The first term in the objective function minimizes the number of controls moved, and the second term minimizes the violations.

Subject to:

1. **Bus Voltage Constraints (from both base and contingencies)**

$$\sum_u \mathbf{S}_u^k * (\mathbf{C}_i - \mathbf{C}_u^0) - \mathbf{x}_{\mathrm{Hi},k} \leq \mathbf{V}_k^h$$

$$\sum_u \mathbf{S}_u^{\mathbf{k}} * (\mathbf{C}_i - \mathbf{C}_u^0) - \mathbf{x}_{\mathrm{low,k}} \geq \mathbf{V}_k^l$$

Where:

$\mathbf{N}$:	sensitivity of control u to constraint *k*
$\mathbf{S}_i^k$:	status of controllable reactive devices
$\mathbf{P}_i$:	slack variable for high limit violation for constraint *k*
$\mathbf{x}_{\mathrm{Hi},k}$:	slack variable for low limit violation for constraint *k*
$\mathbf{P}_k^{max}$:	high voltage limit for bus *k*

2. **ERCOT Special Capacitor Bank Constraints**

Master OFF(C_m=0): $C_m - \sum_i C_{si} \geq 0$

Master ON(C_m=1): $C_m - \sum_i C_{si} \geq -(N-1)$

Where:

$\mathbf{C}_m$:	statues of master capacitor,0,1
$\mathbf{C}_{si}$:	statues of slave capacitor, 0,1

$\mathbf{i}$: slave capacitor i, i=0, 1, 2, N

$\mathbf{N}$: total number of slave capacitor

3. **Regulation Bus Voltage Constraints (Pseudo constraints)**

$$\sum_u \mathbf{S}_u^k * (\mathbf{C}_i - \mathbf{C}_u^0) - \mathbf{x}_{\mathrm{Hi},k} \leq \mathbf{V}_k^h$$

$$\sum_u \mathbf{S}_u^k * (\mathbf{C}_i - \mathbf{C}_u^0) - \mathbf{x}_{\mathrm{low,k}} \geq \mathbf{V}_k^l$$

Where:

$\mathbf{S}_u^k$: sensitivity of control u to regulation bus *k*

$\mathbf{C}_i$: status of controllable reactive devicess

$\mathbf{x}_{\mathrm{Hi},k}$: slack variable for high limit violation for regulation bus *k*

$\mathbf{x}_{\mathrm{low,k}}$: slack variable for low limit violation for regulation bus *k*

$\mathbf{V}_k^h$: high voltage limit for regulation bus *k*

$\mathbf{V}_k^l$: low voltage limit for regulation bus *k*

4. **Transformer tap position limit.**

$$\mathbf{Tap}_{min\ i} \leq \mathbf{T}_i \leq \mathbf{Tap}_{max\ i}$$

Where:

$\mathbf{T}_i$: Tap position for transformer *i*

$\mathbf{Tap}_{min\_i}$: minimal tap position for transformer *i*

$\mathbf{Tap}_{max\_i}$: maximum tap position for transformer *i*

5. **Unit VAR limits.**

$$\mathbf{R}_{min\_i} \leq \mathbf{R}_i \leq \mathbf{R}_{max_i}$$

Where:

$\mathbf{R}_i$: Tap position for transformer *i*

$\mathbf{R}_{min\_i}$: minimal tap position for transformer *i*

$\mathbf{R}_{max\_i}$: maximum tap position for transformer *i*

3.2 Limitations

As mentioned earlier, ERCOT's current SCOPF engine uses LP models, which require linearizing the inherently nonlinear power flow equations. This linearization can introduce inaccuracies, leading to less realistic models of the power system, especially when security constraints are added. To verify the accuracy of the solution, a nonlinear power flow and security assessment must follow the LP optimization, significantly increasing the overall execution time. Additionally, this may require extra LP module runs or manual adjustments by the user to resolve any remaining branch limit or voltage violations.

Another limitation of the ERCOT SCOPF tool is its computation speed. A significant portion of the processing time is spent on contingency analysis, with the entire process requiring up to seven power flow and contingency analysis runs. Typically, this process takes 15-20 minutes, depending on the number of constraints. When manual adjustments are needed, the process can take up to one hour. Due to time and resource constraints, ERCOT's current next-day study process is usually limited to a single time point, typically the forecasted peak demand hour for the next day.

Additional limitations include:

1. **Lack of Temporal Constraints**: ERCOT's Network Operations Model does not yet incorporate temporal constraints (see Section "Temporal Constraints" on page 18).
2. **Limited Reliable Current Operating Plan**: ERCOT lacks a reliable Current Operating Plan beyond the DRUC time frame (24-32 hours). Any SCUC needs a robust method for generating a reliable starting commitment and dispatch, capable of handling various IRR dispatch and load scenarios.
3. **Reactive Reserve Zones**: The ERCOT network model currently does not include reactive reserve zones to maintain reserves.

4. Enhancements for Current SCOPF

In addition to the optimization engine's objective of minimizing control actions, it is important to ensure that the control actions used to resolve thermal and voltage violations do not negatively affect stability limits. Rather than iteratively recalculating or re-verifying stability limits, which consumes significant computational resources and time, additional objective functions should be introduced to inherently maintain or improve stability limits. Some potential techniques are described below:

1. **Maintain Dynamic Reactive Reserves**: Co-optimizing the use of reactive power from dynamic reactive resources (e.g., units, synchronous condensers, STATCOMs, or SVCs) to stay within a smaller leading and lagging range (e.g., 20%) can help maintain dynamic reactive reserves. This, in turn, will stretch the knee of the PV curve and improve transient and voltage stability limits.
2. **Limit Control Movements with Negative Stability Impacts**: Avoid or impose high costs on control actions that are known to negatively affect dynamic stability limits. This ensures that solutions prioritize maintaining stability.
3. **Utilize Reactive Zones**: Ensure that source and sink imbalances do not exceed a certain threshold, which could lead to transfer stability limits being reached.
4. **Include Voltage Drop as a Constrain**t: Enable voltage drop violations as constraints within the CA engine. This helps to identify potential steady-state voltage instability.

While the Dynamic Security Assessment (DSA) manager can include dynamic security assessments like VSAT or TSAT in the study sequence, these assessments would significantly increase computational time. However, they can still be used when a single time point requires further investigation to address any outstanding SOL exceedances that the SCOPF could not resolve.

5. MTSCOPF Development Considerations

Below are some potential improvements that ERCOT desire in the development of MTSCOPF:

1. **Optimize MW and MVAR Controls for the Next 24 Hours**: Co-optimize MW and MVAR controls across multiple hours to minimize overall control movements, resolving thermal and voltage violations while considering temporal constraints.
2. **Improve ESR Forecasting**: While IRR forecasts are relatively accurate, forecasts for ESR, in terms of SOC and injection/absorption, must improve as ESR penetration levels increase. Challenges arise when ESR units inject at high prices, potentially creating scenarios where the case cannot solve due to insufficient generation. Solutions may need to incorporate pricing forecasts.
3. **Enhance Demand Forecasting**: Demand forecasts must also improve to account for the charging behavior of DERs and ESRs. These forecasts should align with both load distribution factors and power factor schedules.

5.1 Temporal Constraints

Multi-time point studies introduce the need for temporal constraints. If the temporal constraints are not modeled and enforced, then solutions may be optimistic or result in undesired wear and tear of transmission and generation devices. Below is the list of temporal constraints ERCOT is interested in:

- For real power controls (mainly generation resources):
  - Maximum number of start-up times over the study horizon
  - Minimum up and down time
  - Maximum up time
- SOC constraints for battery resources

- For reactive power controls (including unit voltage setpoints, transformers tap changes, capacitors, and static var compensators):
  - Maximum number of times a control can move over the study horizon
  - Minimum duration for a control to stay

5.2 User Interface

The multi-hour SCOPF requires a well-designed user interface showing the summary of the multi-hour solution with number of violations identified and number of suggested control movements, and some detailed analyst displays showing the details.

5.3 Performance Requirements

The new MTSCOPF must be robust with reasonable accuracy. "Robustness" means the engine must meet the following requirements:

1. Solve most cases successfully (e.g., over 99% of the time annually)
2. Deliver accurate and consistent results, correctly identifying SOL exceedances, optimizing MW and MVAR controls efficiently, and maintaining numerical precision.
3. Complete its solution within the required timelines (e.g., solve a 24-hour MTSCOPF within one hour).
4. Utilize and respect temporal constraints
5. Be easy to use, maintain, and tune

Additionally, these studies must accurately represent forecasted system conditions. Inaccurate forecasts could result in improper identification of SOL exceedances or unrealistic exceedances being flagged. Temporal constraints should align with real-world operational limits. Furthermore, the SCED and Reactive Power Coordination engines used in the look-ahead study should generate similar results to those used in real-time, assuming reasonably available operating plans and offers. Finally, control actions should be prioritized in a way that simulates real-time operator decisions.

5.4 Security Constrained "Solved" Power Flow

Although many technical approaches use security-constrained "optimal" power flow, finding a truly optimal solution is computationally challenging, particularly due to the non-linearity of the AC power problem. Therefore, the focus should be on achieving a multi-hour, AC security-constrained, "solved" power flow solution – one that prioritizes solving constraints rather than theoretical optimization. Here, a "solved" power flow solution refers to obtaining an AC power flow result that addresses constraints effectively, rather than striving for a mathematically perfect optimization.

Real-time operations often do not achieve both real and reactive power optimization. As such, the goal should not be to find an optimal solution but to solve constraints while maintaining robustness in the solver. The objective function should focus on minimizing control movements rather than reducing losses, with any relaxation applied primarily to the objective function rather than permitting constraint violations. Any constraint violation during a solution should be clearly identified and reported. Frequent violations should be tracked and flagged, as they may indicate underlying issues in problem formulation, available controls, or solver tuning. In real-time operations, system violations cannot be "relaxed," so the solver should reflect this limitation. The degree of relaxation should be adjustable through tunable parameters, allowing flexibility for studies conducted further from real-time while maintaining stricter constraints closer to real-time.

ERCOT should prioritize solutions that respect constraints, ensure robustness, and solve for AC accuracy, while being more flexible with optimization.

6. Current Ongoing Efforts at ERCOT

As of February 2025, ERCOT is enhancing the current SCOPF to provide a MTSCOPF that enables co-optimization for all SOL exceedances (thermal, voltage, and stability). This solution, based on the current single-time-point SCOPF, does not yet incorporate temporal constraints. The new solution will improve the current SCOPF tool and assist operations engineers in conducting more effective multi-hour operations studies. Specifically, it will:

- Set up a real-time process for running periodic, short-term, multi-hour studies (e.g., HR+1 to HR+4)
- Provide the ability to schedule or initiate on-demand multi-hour studies (e.g., 24 hours ahead for the next day)

ERCOT is also evaluating progress made by vendors and peers in the development of such tools, with notable advancements from AEMO and EirGrid.

Recent developments have highlighted the potential of data-driven machine learning methods to address SCOPF's computational challenges [6, 7]. These methods, which can capture complex relationships and quickly predict variables, shift the computational load from online optimization to offline training using extensive historical data. ERCOT is actively seeking collaborative research opportunities with external institutes and universities to explore this approach further.

7. Conclusion

This research paper introduced a new MTSCOPF concept that optimizes both MW and MVAR control actions across multiple time intervals - unlike traditional SCOPF - which operates at a single point in time. By incorporating temporal constraints, the proposed approach more effectively addresses thermal, voltage, and stability limits. The paper also highlighted key computational challenges and explored emerging solutions, including parallel processing and machine learning, to enhance computational performance. Finally, it outlined ongoing efforts at ERCOT and collaboration with external entities to further explore and advance this approach.

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