Use of Generic Transmission Constraints in ERCOT

Table of Contents

1. Introduction

In ERCOT, the existing market tools (e.g. Security Constrained Economic Dispatch (SCED), Reliability Unit Commitment (RUC), etc.) are primarily designed to efficiently determine the lowest cost Real-Time system dispatch while adhering to pre- and post-contingency thermal overloads of Transmission Elements. However, there are additional operating limits that must be respected in order to maintain grid reliability. As a result, Generic Transmission Constraints (GTCs) are used to monitor flows between areas of the ERCOT Grid and control those flows using market-based mechanisms in order to maintain stability and other non-thermal reliability limits that would not otherwise be considered in market mechanisms. This translation of non-thermal limits into GTCs, and then the use of market mechanisms to control the GTCs ensures that the stability and other non-thermal constraints on the system are managed in an efficient manner.

This white paper provides an overview of system stability phenomena, the evolution of ERCOT Grid characteristics, identification of GTCs and the use of GTCs to address those stability phenomena and Grid characteristics. It also describes issues related to reliably operating the System within the GTC construct.

2. Background on System Stability

Dynamic studies, which are used to identify most stability limits, require detailed dynamic models of ERCOT Facilities and significant resources and time to conduct the studies. Most GTCs are used in the ERCOT System to maintain stability, therefore, this section provides an overview of the system stability challenges that have been addressed using GTCs. Also, a GTC may be used to constraint different stability issues depending on the system conditions. By describing the types of stability issues, the causes of instability, and options for mitigation, it will become clear that the same underlying conditions, most notably heavily loaded high-impedance transfer paths, tend to exacerbate many of these stability challenges. As such, limited benefit may be realized from mitigation options that address only one aspect of stability.

2.1. Voltage Stability

Voltage stability issues are generally characterized by a lack of sufficient reactive power to maintain acceptable voltage levels. Such conditions are commonly encountered when a load center is importing a large amount of power or a generation pocket is exporting a large amount of power through long transfer paths, which tend to have high aggregate impedance and consume large amounts of reactive power. Generally, there are two types of voltage stability:

- Steady State Voltage Stability: the ability to maintain acceptable voltage levels under normal and outage conditions. Power flow based simulation such as PV analysis without dynamic models is generally used to assess steady state voltage stability. The Voltage Security Assessment (VSAT) application is implemented in ERCOT for real-time operation support.
- Transient/Dynamic Voltage Stability: the ability to maintain acceptable voltage recovery in the first few seconds immediately following system disturbances and return to normal conditions. Dynamic simulation, including models that accurately reflect dynamic response, is required to assess transient/dynamic voltage stability. Currently, dynamic simulation applications like PSS/e and TSAT are used as off-line tools. ERCOT plans to implement Real-Time TSAT to be capable of assessing dynamic stability in the real-time

operation. In the absence of Real-Time TSAT, ERCOT performs off-line dynamic studies to determine dynamic voltage stability limits and apply them in Real-Time operation.

Options for mitigating voltage stability issues include but are not limited to reducing the flow through the high impedance transfer paths, adding sources for reactive compensation (static and/or dynamic devices) and upgrading the transmission grid to reduce network impedance across critical transfer paths. It should be noted that the effectiveness of adding reactive compensation to a system reduces as the system becomes increasingly compensated.

2.2. Angular Stability

Angular stability issues are generally associated with the potential for synchronous generators to lose synchronism with the grid. When a transmission line fault occurs near the generator, low voltage prevents the delivery of power from the generator. Energy that was previously being delivered to the grid accelerates the generator shaft until the fault is cleared and power delivery to the grid can resume. Depending on the fault severity and duration as well as the post-disturbance network connections, the generator may or may not maintain synchronism with the grid. Options for mitigating angular stability issues include but are not limited to reducing flow through high impedance transfer paths, improving protection systems to reduce fault clearing times and transmission upgrades that add outlet paths or reduce post-disturbance network impedance as seen from the generator.

2.3. Oscillatory Stability

Oscillatory stability issues are generally characterized by either a synchronous machine oscillating against the system (local mode) or a group of synchronous machines oscillating against another group of synchronous machines (inter-area mode). When an oscillation occurs, the inverter-based power system devices in the vicinity could be affected and participate in the oscillation. The system is most susceptible to oscillations when there are high power transfers across high impedance paths and relatively weak ties between the components that are participating in the oscillation. Options for mitigating oscillatory stability issues include but are not limited to reducing flow on high impedance transfer paths, adding power oscillation damping (POD) control functions to power system devices[1], and upgrading the transmission grid to reduce network impedance across critical transfer paths.

2.4. Control Stability

Control stability issues are generally associated with the potential for inverter controls to fail under conditions of low system strength, which is often described in terms of a short circuit ratio (SCR). Most IBRs require connection to a strong grid for proper operation. IBRs that experience control instability may exhibit oscillatory behavior and/or trip off. Options for mitigating control stability issues include improving the relative system strength so that voltage is less sensitive to changes in reactive power. This can be accomplished by reducing IBR output, installing devices that contribute fault current (e.g. synchronous condensers), installing dynamic devices to improve voltage control (e.g. SVCs or STATCOMs), and upgrading the transmission grid to reduce network impedance. Advances in IBR technology may allow reliable operation over a wider range of system strength conditions in the future.

[1] In ERCOT, synchronous generating units are required to have power system stabilizers (PSS) which mitigate oscillatory behavior.

3. Stability Constraint Identification

ERCOT uses a variety of reliability studies to identify relevant stability and other non-thermal system limitations. Planning assessments, interconnection studies, Quarterly Stability Assessments (QSA) and operational studies assess different time horizons, with different generation resource assumptions, to assess impacts of new and existing generation on grid limitations. The identified system limitations may be binding at all times, or may only be temporarily relevant during specific operating conditions. If these system limitations can be mitigated by reducing the output of specific resources in order to limit power flow into or out of an area, then these limits are quantified using the appropriate assessment tools.

3.1. Planning Studies

The Full Interconnection Study (FIS), which is performed by the interconnecting TSP, represents the first practical opportunity to identify potential stability constraints associated with the installation of specific new generation. Detailed dynamic models, the parameters of which can have a significant impact on stability study results, typically are not available prior to the FIS. Planning studies evaluating stability with assumed models and locations may help identify potential future stability challenges but often cannot support detailed or strong study conclusions.

ERCOT conducts annual stability assessments to evaluate stability across the system based on applicable NERC and ERCOT reliability criteria. Additional ad hoc studies are also conducted to focus on particular areas or conditions as needed. These studies generally consider generation that has satisfied criteria specified in Planning Guide Section 6.9 and has submitted usable dynamic models. Identified stability constraints are not considered reliability violations if they can be resolved through re-dispatch of generation. Transmission upgrades to address such constraints are implemented when ERCOT economic planning criteria are satisfied.

3.2. Quarterly Stability Assessment (QSA)

The QSA is conducted every three months to assess the impact of planned Generation Resources (GRs), Energy Storage Resources (ESRs) and Settlement Only Generators (SOGs) connecting to the ERCOT Transmission Grid on existing or new non-thermal grid constraints. The QSA includes all GRs, ESRs and SOGs with planned Initial Synchronization during a specific three month period. The QSA establishes clear manageable timelines for studying and implementing GTCs before Initial Synchronization.

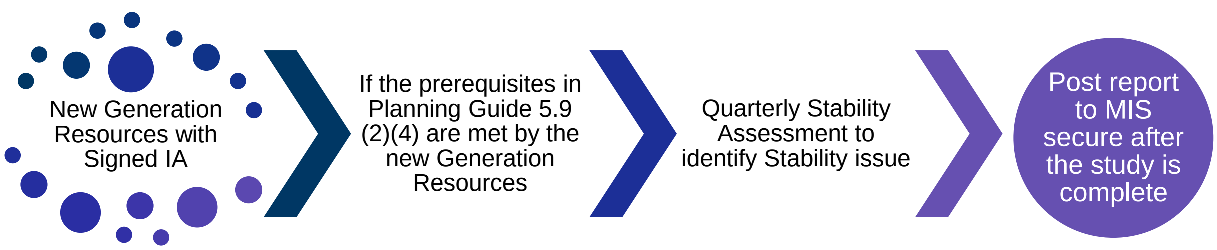

Figure 1: High General Process of Quarterly Stability Assessment

While an individual FIS stability study focuses on a particular new generating unit connecting to a specific location, a QSA provides an assessment of all new units expected to synchronize to an area of interest, as well as larger regional issues. QSA studies are performed using the most recently approved Dynamics Working Group (DWG) stability cases, and ERCOT will update these DWG cases as needed to accurately represent the intended operations study horizon. The QSA evaluates dynamic stability based on criteria included in ERCOT Planning Guide Section 4 and the NERC TPL-001-4 reliability standard. ERCOT derives the conditions to be studied in the QSA by considering the results of the FIS stability studies for GRs, ESRs and SOGs. Conditions other than those identified in the FIS stability studies may also be studied. The QSA builds on information developed in the FIS stability studies and informs the actual implementation of GTCs.

QSA results are used to identify stability issues that would affect existing GTCs or show a need to create new GTCs to manage these issues. QSA results should be interpreted as an update/addendum to the FIS stability study. Further, QSA results should not be interpreted as the final GTLs for any specific GTC. The QSA is not meant to identify interface definitions for any specific GTC.

For every potential non-thermal system constraint identified in the QSA, ERCOT will perform a GTC assessment to determine a GTC interface and the appropriate GTLs. Changes to the Initial Synchronization dates of specific units may cause a GTC assessment to be moved to a different time period (i.e., to move to being reviewed based on a later QSA). Depending on the Initial Synchronization date, the GTC study could rely on multiple QSAs as illustrated in Figure 2.

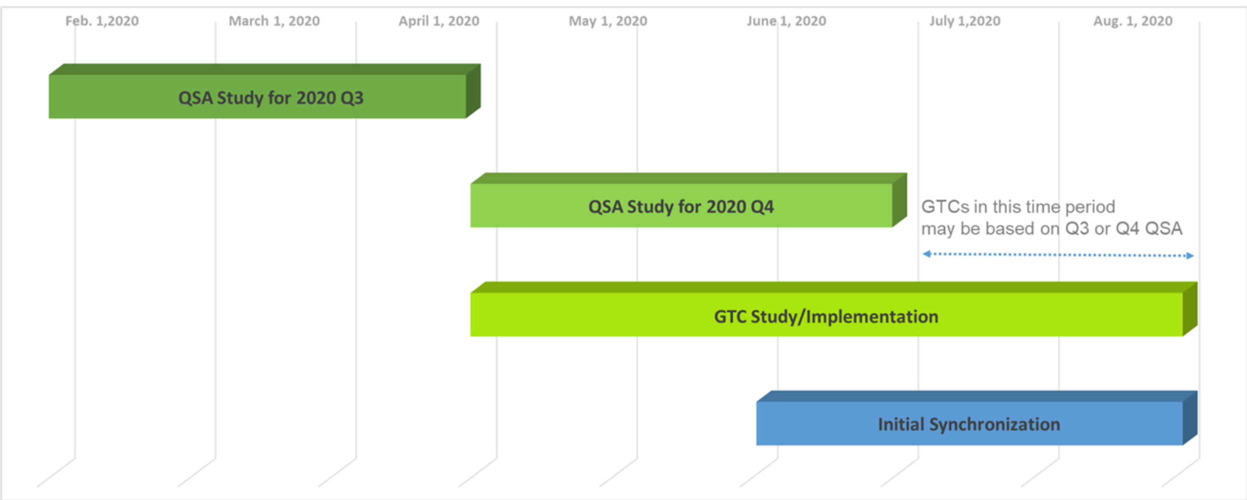

Figure 2: QSA/GTC Process Timeline

3.3. Operational Analyses

There are three categories of reliability analyses within the operational horizon that may indicate instability or other non-thermal reliability constraints – Outage Coordination, Next-Day, and Real-Time assessments. Typically, a non-thermal constraint will be indicated in these studies by either an unsolved contingency which causes the non-linear power-flow solution to diverge, or a thermal overload that exceeds cascading outage criteria[2].

[2] Cascading criteria is outlined in the ERCOT System Operating Limits Methodology. For the purpose of this white paper, post-contingency thermal loading greater than 125% of the Emergency (2-Hour) Rating would trigger a cascading assessment.

In Outage Coordination assessments, if an Outage is determined to cause an unsolved contingency or cascading outages post-contingency, the Outage will not be approved.

In the Next Day assessments, if there is an unsolved contingency, analyses are performed to determine if the issue is due to a Forced Outage, or if the contingency can be resolved with additional reactive support, such as from additional committed generation capacity. An operating plan is proposed and communicated to the TSPs affected by the unsolved contingency, as necessary. Similarly, if there is a thermal overload that exceeds cascading outage criteria, an operating plan is proposed and communicated to the affected transmission companies.

In Real-Time assessments, the same assessment is performed as would be done in the Next Day studies. If ERCOT determines that the instability or cascade condition is not due to an Outage, or multiple Outages, a Watch is declared in Real-Time and an operating plan is coordinated between the ERCOT System Operators and the affected transmission companies which can be used until a permanent solution is determined.

If a new stability constraint is identified in Real-Time, a GTC will be implemented in the ERCOT System as soon as practicable so that SCED can be used to provide a market mechanism for addressing the instability.

4. Use of Generic Transmission Constraints (GTCs)

4.1. What is a GTC?

As defined in the ERCOT Nodal Protocols, a GTC is a transmission constraint made up of one or more grouped Transmission Elements that is used to constrain flow between geographic areas of ERCOT for the purpose of managing stability, voltage, and other constraints that cannot otherwise be modeled directly in ERCOT's power flow and contingency analysis applications. In other words, a GTC is a pre-defined collection of transmission elements, over which the aggregate power-flow will be subject to a defined limit in Real-Time in order to maintain grid reliability.

A Generic Transmission Limit (GTL) is a value calculated for a given GTC that represents the system operating limit for that GTC under a given set of system conditions. GTLs represent pre-contingency flows that need be maintained to prevent instability or other non-thermal reliability issues if a given contingency were to occur. The GTL for a particular GTC may change based on different system conditions (e.g. transmission outages) and, the GTL may be set based on different instability phenomena. The GTL may be calculated in Real-Time by online tools, or be pre-determined for a variety of system conditions based on offline studies. If more than one instability phenomenon could manifest on a particular GTC under current conditions, (usually due to different critical contingencies that might occur), the GTL is set to the most restrictive limit.

In the ERCOT Network Operations Model, a GTC can be modeled as a group of one or more Transmission Elements. This grouping is made to measure System flows near an area of importance where regional, or broader area, monitoring of System conditions is desired. Traditionally, this area of importance is a local area or region where non-thermal system operating limits exist, typically system instability regions. GTCs monitor the sum of the flows on the Transmission Elements that make up the GTC and provide for a means to control those flows in the various ERCOT markets to assigned Generic Transmission Limits (GTLs).

4.2. How a GTC is used?

GTCs are used in the ERCOT System in the same way thermal constraints are managed. Each GTC is its own constraint, and its GTL is enforced as a base case constraint. This is true in the Congestion Revenue Rights (CRR) auctions, the Day Ahead Market (DAM), and Real-Time Market (Security Constrained Economic Dispatch, or SCED). The most accurate GTLs available at the time each market is conducted are used for that market. To provide market participants with visibility into the potential value of a GTL, a GTC Methodology[3] is posted on the ERCOT Market Information System (MIS) Secure Area for each GTC, and that Methodology contains a set of default GTLs for various system conditions.

In the CRR auctions, GTLs are determined as part of the normal auction model process. The GTLs are determined by either using the offline study results based on the applicable GTC Methodology or by running studies with the available tools based on the system conditions and network topology reflected in the auction models. Given that the auctions are conducted for time periods as far as three years into the future, there is more potential for the auction network topology to not reflect actual, real-time system conditions. As a result, transmission capacity in the CRR auctions is generally scaled down to recognize the additional uncertainty and prevent potential overselling of CRRs in the auctions.

GTLs for the DAM are calculated from an operational study that is performed the day before the DAM executes (i.e. two days before the Operating Day for which the DAM is being run). This study calculates GTLs using the most up to date system information and passes those limits to the DAM operators. When possible, this operational study is performed using online tools to provide a more accurate GTL than what is in the GTC Methodology[4] to aid in improved convergence between the DAM and Real-Time Markets.

In Real-Time, GTLs are updated every ten minutes using online tools, when possible, to ensure that ERCOT System operators are managing these non-thermal limits based on Real-Time system conditions. For GTCs where the GTLs cannot be updated using online tools, the Real-Time GTLs are updated using a static table.

In SCED, the aggregate impact on the elements of the GTC from an injection by each Resource is used to determine which units to decrease or increase output to stay within the limits of the GTC. For example, if two Resources have the same offer, but the aggregated shift factor on the elements of the GTC is higher for one Resource than the other, the one Resource with the higher shift factor will be dispatched down ahead of the other Resource to relieve the constraint by a greater amount at a lower cost. It is important to design the GTCs in such a way that not only is the flow on the elements of the GTC good indicator of the whether the stability issue is becoming a concern, but that the proper Resources are dispatched to address the stability issues. Offers then allow SCED to find the most economical way of controlling to the GTL.

5. GTC Determination

The goal of determining how to design a specific GTC is to maintain the reliability of the system efficiently. The design must consider the specific details of the non-thermal phenomenon, the

[3] https://mis.ercot.com/misapp/GetReports.do?reportTypeId=11425
[4] Most GTLs are static, based on off-line studies; however some GTLs can be calculated using near-real-time tools based on the updated system conditions that can better reflect the anticipated system conditions.

power transfer that can be controlled to protect against the phenomenon, the transmission elements that should be monitored and used to control those transfers, the Resources that SCED will possibly dispatch to control the flows on the GTC, how SCED will dispatch the system to stay within the GTLs, and the ability to model the GTC in the ERCOT System. In some cases, multiple GTCs are needed to meet the reliability need. Generally, the following are considered to determine GTCs:

- A GTC is defined in a way so that the system can control Resources based on their impact on relieving the instability phenomenon, to the extent these differences in impact can be modelled in the market tools. For example, if two generators have the same impact on the instability phenomenon, but have radically different shift factors on a GTC, the GTC will need to be revised.
- Depending on the type of instability for which the GTC is needed, online tools and applications may need to be able to calculate limits or lookup offline calculated limits in or near Real-Time based on current system conditions. This may also impact how a GTC is defined.
- The definition of the GTC needs to properly include the Transmission Elements that can effectively resolve the instability phenomenon through controlling the flow on the lines that make up the GTC.

GTCs can be either “closed loop” or “open loop.” A closed-loop GTC encircles a region of the system such that the Resources in the region have a 100% shift factor on the flow on the GTC, either helping (negative) or hurting (positive). The shift factors do not change as the system topology changes because the GTC definition “contains” the region of concern. An open-loop GTC establishes a cut plain across a small region of the system, very similar to a typical thermal constraint. With an opened loop GTC, Resources on one side of the GTC may not have the same shift factors on the GTC. This characteristic is helpful when trying to efficiently protect against an instability where some Resources have a higher impact.

None of the elements that make up a GTC can be behind a Resource’s Resource Node. This is because SCED generally dispatches Resources based on connectivity nodes, and if a GTC is between the Resource Node and the Resource’s connectivity node, then there is a potential for convergence issues between CRR, DAM, and Real-Time, even at equivalent dispatch levels.

As previously stated, a GTC is modeled to measure the sum flows on the Transmission Elements that make up the GTC definition. But, *how* the GTC elements are selected is just as important as which elements are chosen. Currently, for a GTC associated with generation injection instability, the GTC is defined at the point of interconnection for the impacted generator(s). For a GTC associated with serving load, the GTC is defined as close to the area of instability as possible. For a GTC associated with dynamic instability, the GTC is defined at the predicted area of separation. The reason for doing this is so that the impact of the GTC is limited just to the area for which the instability exists.

6. GTC Implementation and Communication

6.1. GTC Implementation

Once a specific GTC is determined, the information has to be added to the ERCOT system models; applications and situational awareness tools need to be modified and tested; ERCOT

System operators need to be trained on how to use the GTC; and a Methodology has to be developed and posted on the ERCOT MIS Secure Area.

To physically model the GTC in the Network Operations Model, a Network Operations Model Change Request (NOMCR) is required. Preferably, a NOMCR needs to be submitted at least 90 days prior to the model load for which the change in the NOMCR is needed. However, most GTCs are determined inside of 90 days and require an interim update NOMCR to be submitted. In most cases GTC-related NOMCRs can be implemented with a lead time of only three to four weeks.

GTLs are determined based on the output of Real-Time applications, or using a pre-determined static table of limits based on representative system topologies. Real-time applications are used where possible, as they tend to provide the most accurate GTLs based on actual system conditions. If a Real-Time application is used, the proper system study case for that application needs to be developed and tested before being implemented. Even if a Real-Time application is used, a static table of limits will be developed, in the event the Real-Time applications become unavailable.

Once the GTC is in the Network Operations Model, the control room situational awareness tools must be updated, and Real-Time information needs to be made available to the transmission companies impacted by the GTC per NERC Reliability Standard FAC-014 requirements. This process typically takes about a week to implement, given the complexity of the situational awareness tools and staff availability, as the situational awareness tools are manually created and supported, and as such, cannot be built until the GTC-related information is present in the online System model. After the situational awareness tools are updated, and the GTC-related modeling and application tuning is complete, ERCOT System operators are trained on the GTC, the reliability problem it is addressing, how to interpret the situational awareness tools, and how to enforce the GTLs.

The Network Operations Model update process also initiates inclusion of the GTC in the CRRs auctions, DAM, and RUC.

6.2. GTC Communication

Given that the ultimate goal of a GTC is to provide a market solution to a reliability problem, it is therefore highly market-sensitive in nature. Additionally, the details of the GTC may be considered as Critical Energy Infrastructure Information (CEII). CEII data is confidential in nature, and therefore when GTC information is communicated, the details need to be redacted to protect the critical information but also transparent enough to provide the market an understanding of the need and use for the GTC. Section 3.10.7.6 of the current ERCOT Nodal Protocols outlines much of the process for communicating GTC-related information. When a new GTC is implemented or modifications to an existing GTC are made, ERCOT is required to issue a Market Notice, typically 2 days in advance, as well as post a redacted version of the GTC Methodology to the MIS Secure Area. Normally, ERCOT does not begin enforcing a new GTC, or changes to an existing GTC, until a Market Notice is issued; however in some cases the GTC may need to be enforced more quickly, such as when system conditions necessitate the development of a GTC in Real-Time. In such a case, an Operating Condition

Notice[5] (OCN) is issued so that the market is aware of the new GTC implementation, and then a Market Notice is issued after the fact, once the GTC Methodology documentation is developed and posted on the MIS Secure Area.

The GTC Methodology is a document that contains all the relevant details pertaining to the GTC, and includes the following items:

- The stability issue for which the GTC is being implemented
- Identification of the Transmission Elements that make up the GTC definition
- The study conditions used in the GTC assessment, including contingencies assessed, System load levels, and any prior Outages that were considered
- The results of the conditions studied
- The methodology for calculating limits for the GTC
- How to use any static table of limits in the event Real-Time applications cannot be used
- Potential alternatives for exiting the GTC
- Additional specific details as necessary to meet NERC Reliability Standard FAC-014 Requirements

7. GTC Alternatives Identification

ERCOT Nodal Protocol Section 3.10.7.6 (7) requires ERCOT to post alternatives for exiting a GTC within 180 days of the effective date of a GTC. GTC exit alternatives are included in the GTC methodologies posted on the MIS. ERCOT, in consultation with the TSP, develops an exit alternative that would allow the GTC to be retired. As the system evolves, the adequacy of GTC exit alternatives are reviewed as necessary.

Most GTC exit alternatives require significant transmission upgrades. These exit alternatives provide an indication of the scope and scale of projects necessary to exit the GTC and should serve as a reference for implementation of transmission upgrades. If all reliability criteria can be met while respecting the GTCs, the identified GTC alternatives are considered as potential economic-driven projects and can be included in the planning studies (e.g. Regional Transmission Plan or Regional Planning Group Review) to evaluate societal benefit through production cost analysis. Per ERCOT Nodal Protocol Section 3.11.2, if this production cost savings equals or exceeds this annual revenue requirement for the project, the project is economic from a societal perspective and will be recommended.

8. Issues with Volume and Complexity of GTCs

More recently, the ERCOT region has been experiencing significant growth in the interconnection of Inverter-Based Resources (IBRs). The number and complexity of stability limits on the ERCOT System has also increased. Figure 3 shows the total effective GTCs at the end of each year since 2014. In addition, increasing number of new planned generation projects meet Planning Guide 6.9, Addition of Proposed Generation to the Planning Models, requirements close to the deadline of QSA which is typically within 12 months of the

[5] When a new GTC is implemented in real-time, an OCN is required pursuant to Section 3.10.7.6(6) of the ERCOT Nodal Protocols.

Commercial Operation Date (COD) of the planned projects. As such, the impact of these new generation projects cannot be assessed in the planning horizon which generally focus on the system conditions at least one year ahead of the real-time operation.

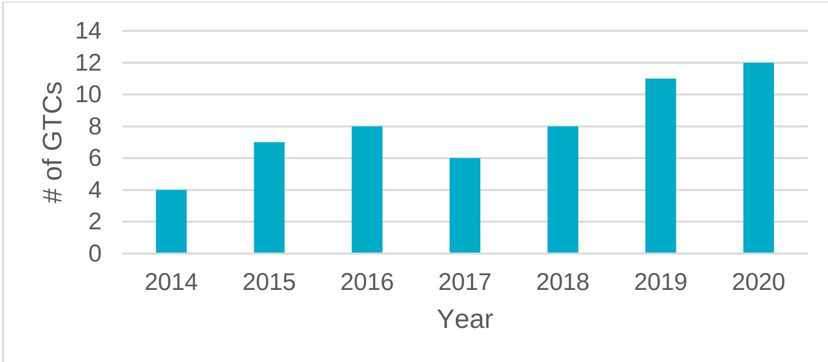

Figure 3: Effective GTCs since 2010

8.1. Situational Awareness Issues with Increasing GTCs

Given that both manual constraints and thermal constraints exist on the same Energy Management System (EMS) screen within Transmission Constraint Manager (TCM) application in the ERCOT control room, as the number of GTCs in use increases, the number of constraints needing System Operator action increases, especially during stressed system conditions. Also, as the number of GTCs increase, the effectiveness of situational awareness tools are negatively impacted.

8.2. Increasing GTC Complexity

As the volume of GTCs increases, so does the complexity. The first example is the "nested GTC" condition. GTCs are layered on top of each other, as a result of the interaction of local and regional instabilities. The illustration in Figure 4 is a generalized representation of an actual system condition on the ERCOT grid. For nested GTCs, SCED optimizes the dispatch such that all generators are dispatched to respect all three GTCs.

The second example is the efficacy of an Outage's impact on a GTC. The nature of a given instability issue, combined with the topology of the System, GTC definitions and their limits, may vary based on Outages in the System. The illustration in Figure 5 is another generalized representation of an actual system condition on the ERCOT grid. The instability is associated with the aggregate generation export from Generators 1 - 5 into Stations A and F, and therefore the GTC is defined as the sum of flows on the lines from Station B to A and Station E to F. However, as Outages occur between Stations A and E, denoted as Xs in Figure 5 for illustration purposes, the System is cut so that different generators inject into Stations A and F depending on where the System is split. A potential option to address this issue is to have one GTC for each possible combination of Outages between Stations A and F. As a result, a variable-definition GTC presents complexity that currently cannot be accounted for in the ERCOT System.

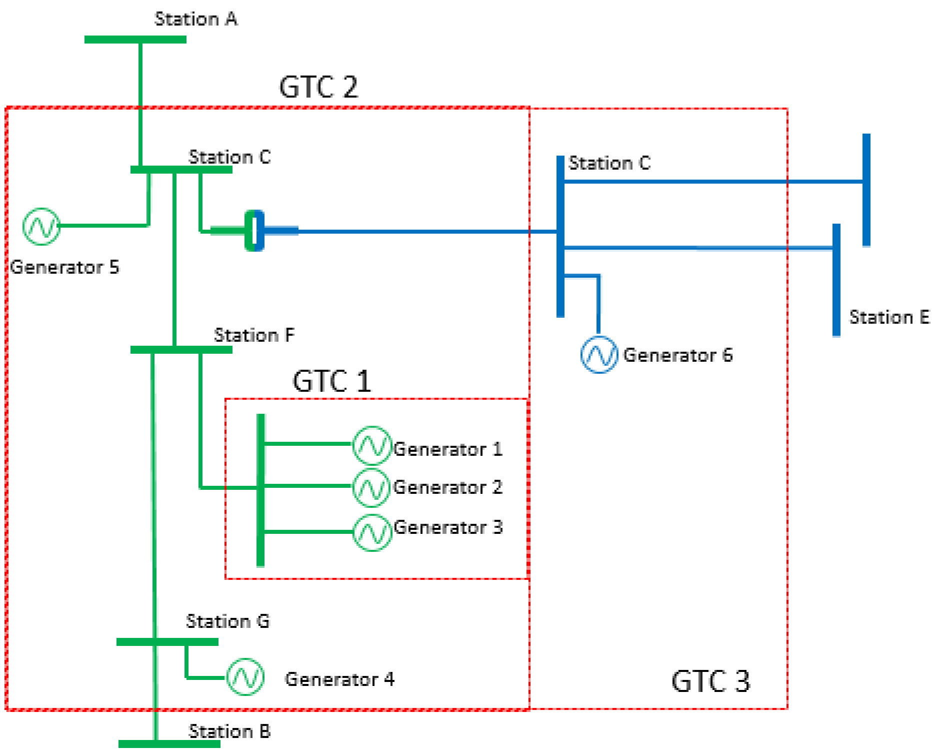

Figure 4: An example of nested GTCs

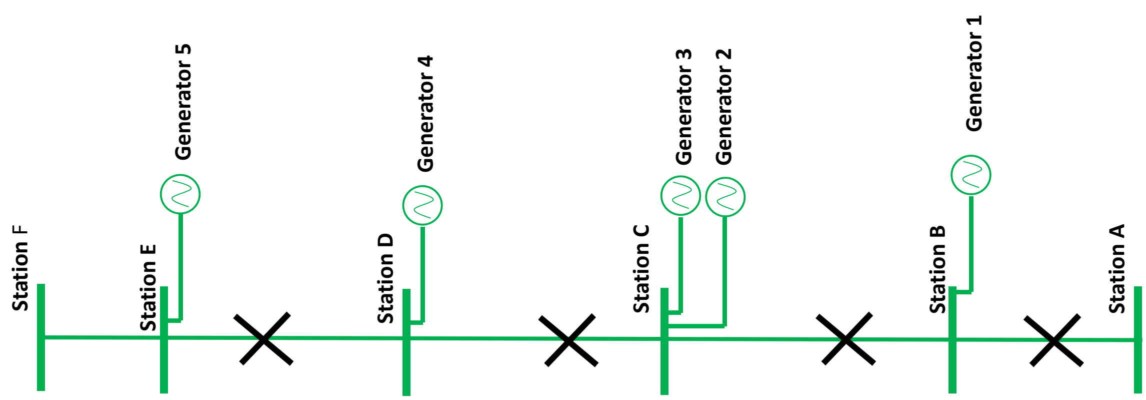

Figure 5: An example of GTCs affected by Outages