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Grid Enhancing Technologies

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Acronyms

AAR	ambient adjusted ratings
DLR	dynamic line ratings
FACTS	Flexible Alternating Current Transmission Systems
FERC	Federal Energy Regulatory Commission
GETs	Grid-Enhancing Technologies
NTO	Network Topology Optimization
OPF	optimal power flows
SLR	static line ratings
STATCOM	Static synchronous compensators
SVC	Static Volt-Amps Reactive (VAR) compensators
SYNCON	Synchronous condensers
TCSC	Thyristor-controlled series capacitors
TS	Transmission Switching
VAR	Volt-Amps Reactive
VSC	Voltage source converters

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BULK POWER SYSTEM FLOW CONTROL

1. GRID ENHANCING TECHNOLOGIES OVERVIEW

On July 28, 2023, the Federal Energy Regulatory Commission (FERC) issued Order Number 2023[a], targeting an improved generation-interconnection process in the United States. An amendment to this order, FERC Order No. 2023-A[b] provided further clarifications, but maintained the same requirements for consideration of alternative transmission technologies. These alternative transmission technologies represent capacity expansion technologies other than network expansion through conventional methods like the construction of new transmission lines. These alternative transmission technologies provide system improvements and help expand bulk-power system capacity without the requirement of the prolonged process to construct new transmission facilities. Transmission providers must consider these technologies, several of which fall under the category of Grid Enhancing Technologies (GETs). Within the purview of FERC, the definitions of GETs to consider are:

- Static synchronous compensators (STATCOMs), which can provide or absorb reactive current to regulate voltage at the point of interconnection with the power grid
- Static Volt-Amps Reactive (VAR) compensators (SVCs), which compensate for the reactive-power demand of load connected to a power system and stabilize voltages
- Advanced power-flow control devices, which encourage or restrain power flow to mitigate overloaded lines and encourage better use of underutilized corridors within the transmission grid
- Transmission switching, which can redirect power flows from one transmission line to another via topology modification, allowing for the routing of power flows around areas with high congestion
- Synchronous condensers (SYNCONs), which can improve the transmission-line power factors by producing or absorbing reactive power
- Voltage source converters (VSCs), which can generate alternating current (AC) voltages that support the regulation of grid voltages
- Advanced conductors, electric conductors made of advanced aluminum alloys, steel, and/or modern composite core that can be used to significantly improve transmission efficiency

a FERC Docket No. RM22-14-000; Order No. 2023, Improvements to Generator Interconnection Procedures and Agreements, 184 FERC ¶ 61,054, issued July 28, 2023.

b FERC Docket No. RM22-14-001; Order No. 2023-A, Improvements to Generator Interconnection Procedures and Agreements, 186 FERC ¶ 61,199, issued March 21, 2024.

- Tower lifting, which raises a transmission tower to permit the transmission line to meet clearance criteria while carrying additional capacity, alleviating sag limitations and allowing the line to operate at its design rating.

FERC reaffirmed requirements to integrate a subset of these technologies as part of the long-term transmission planning process in FERC Order No. 1920[c]. This order focuses on implementing new requirements for the consideration on regional transmission expansion. In the order there is a requirement to consider the impact that dynamic line ratings (DLR), advanced power flow control devices, advanced conductors, and transmission switching can provide to address projected grid future states and provide solutions that address the challenges associated with the construction of new transmission lines. This is a timely requirement as only 55 miles of new transmission lines operating at voltages of 345 kV and above were constructed in 2023[d]. Although the above are described as technologies requiring consideration in FERC jurisdictional regions, many systems can benefit from cost and time savings through the implementation of GETs and other advanced transmission solutions.

Another technology which has received significant attention due to FERC Order No. 881[e] and the amendment FERC Order No. 881-A[f] is Ambient Adjusted Ratings (AAR). FERC has issued an ANOPR that would act as an extension to FERC Order No. 881 and 881-A which considers potential implementation requirements for DLR. AAR & DLR are facility rating processes that require ratings to be calculated based off of certain environmental conditions in which transmission facilities operate. While these no longer fall under FERC's definition of a GET, they are often grouped in the same category as the above listed technologies due to the ability of variable line ratings to increase transmission capacity in the operation timeframe. Ambient Adjusted Ratings account for the hourly ambient temperature along a line and daytime/nighttime solar heating to determine line capacity less conservatively than the fixed capacity limit, while Dynamic Line Ratings use more advanced physical heat transfer equations to the same end but with more accuracy. AAR and DLR have been included as GETs in this paper.

c FERC Docket No. RM21-17-00; Order No. 1920, Building for the Future Through Electric Regional Transmission Planning and Cost Allocation, 187 FERC ¶ 61,068, issued May 13, 2024.

d N. Shreve, Z. Zimmerman, R. Gramlich, "Fewer New Miles: The US Transmission Grid in the 2020s," Americans for a Clean Energy Grid, July 2024.

e FERC Docket No. RM20-16-000; Order No. 881, Managing Transmission Line Ratings, 177 FERC ¶ 61, 179, issued December 16, 2021.

f FERC Docket No. RM20-16-001; Order No. 881-A, Managing Transmission Line Ratings, issued May 25, 2022.

Figure 1. Reenergizing the transmission system.

The above discussion presents the current regulatory actions that are targeted towards the implementation of new processes and technologies to provide transmission solutions. To provide context behind the impetus for these changes to process one can refer to the Lawrence Berkeley National Laboratory's "Queued Up" analysis,[g] which demonstrates the significant levels of generation seeking interconnection with the grid that have been delayed due to the conventional interconnection processes.

FERC issued Order No. 2023 with the intent to improve the processes and implement penalties for potential delays beyond the schedules provided.

Several overlapping factors brought these considerations to bear. These include significant delays preventing greenfield (new build) transmission expansion, electrification growth, increasing rates of electric vehicle adoption, industrial manufacturing, data centers, and other large load interconnections. These factors translate into continued, and sometimes highly localized, load growth on the electric grid. Meeting these new demands requires the interconnection and the dispatch of new generation to meet resource adequacy requirements, while making better use of the existing transmission grid capacity. This is a pressing concern as loads can be interconnected more quickly than new transmission can be added to existing infrastructure. This means that transmission capacity requests quickly outpace solutions involving transmission capacity expansion.

Adding to this complexity, many new generation resources added to the system are renewable energy resources. These are located where their energy sources (i.e., wind and sunlight) are abundant, often remote from load centers, requiring additional transmission capacity to be reserved to facilitate new transfers. Other common interconnection

g J. Rand, N. Manderlink, W. Gorman, et al, "Queued Up: 2024 Edition, Characteristics of Power Plants Seeking Transmission Interconnection as of the End of 2023," Lawrence Berkeley National Laboratory, April 2024.

configurations entail looping renewable resources into existing transmission facilities, further increasing current flow on the existing transmission system. These combined circumstances have introduced congestion, voltage stability concerns, and operational challenges to the bulk power system.

Transmission planning has shown intensifying reliability concerns derived from increased congestion and transmission system bottlenecks, as well as instabilities due to excessive flows after system contingency events. Transmission planners, owners, and operators have increasingly recognized the need to add fast acting control methods to regulate congestion and support reliable and stable system operation after critical system events. GETs provide the ability to capitalize on opportunities within the operational timeframe. GETs alone do not represent transmission-capacity expansions; rather, they are optimizations of the existing grid. Reconductoring with advanced conductors and tower lifting are the only solutions included in the FERC list of alternative transmission technologies that would represent permanent increases in transmission capacity, rather than optimizations of the use of existing capacity. In certain use cases, the installation of equipment like SYNCONs or shunt-connected flexible alternating current transmission systems (FACTS) can increase the ability to transfer power, and this further optimizes existing capacity to make full use of constructed energy infrastructure.

1.1 Flexible Alternating Current Transmission Systems

The FACTS family consists of shunt and series installed systems that provide controllability of power systems, where most use power electronics converters. There are two basic converter technologies, that is, thyristor-based Line Commutated Converter (LCC), which are more mature dating back to the 1960s, and thyristor-based Voltage Source Converters (VSC), first implemented in utility applications in the early 1990s. FACTS have been primarily implemented for dynamic issues given the speed and repeatability of their operation and focus their control of three main variables in the power system, namely voltage, angle, and impedance, which collectively influence the flow of power through an element or system.

The most common examples of FACTS controllers are:

- Fixed Series Capacitor (FSC): series connected
- Static Var Compensator (SVC): shunt connected
- Static Synchronous Compensator (STATCOM): shunt connected
- Thyristor Controlled Series Capacitor (TCSC): series connected
- Static Synchronous Series Compensator (SSSC): series connected
- Unified Power Flow Controller (UPFC): series and shunt connected

FACTS have proved to be cost-effective solutions to a wide range of power system needs and have provided the ability to delay new transmission line construction by increasing transmission capacity on existing lines and/or providing dynamic control and compensation of system voltages. FACTS systems are available in different forms, such as those listed above.

1.1.1 Shunt Connected FACTS Devices

SVC and STATCOM are classified as shunt dynamic reactive compensation devices that rapidly inject or absorb volt-ampere-reactive (vars) to support power system voltage during and immediately following system disturbances. SVCs employ thyristor-based switching devices that are line-commutated and require the thyristor gate to turn on every half cycle (or as required by the control system).

STATCOMs employ insulated gate bipolar transistors (IGBT) or integrated gate commutated thyristors (IGCT) that are self-commutated, allowing the switching device to be turned on and off independent of source voltage. STATCOM output is independent of voltage, while SVC output is a function of the voltage, meaning that STATCOM power output is reduced proportionally with voltage while SVC output is reduced by the square of the voltage. Additionally, as STATCOM control is facilitated through switching devices they can provide faster control response as compared to SVC technology, with potential for faster response times and improved performance in weak power system networks[h]. Additional discussion of shunt connected FACTS devices can be found in the "Shunt Connected Flexible Alternating Current Transmission Systems (FACTS) Versus Synchronous Condensers" white paper.

1.1.2 Series Connected FACTS Devices

Series connected FACTS, which have been around for more than 70 years, provide direct power flow control options for the AC network and allow for the optimization of loading existing transmission facilities. Series connected FACTS function by regulating the impedance or the angle between two stations as a method of directly controlling the flow of power across the transmission facility where the series FACTS device is installed. Series FACTS can be used to increase the amount of power that can be transferred between areas and increase system stability under these heavier transfers. These devices can be used to either dissuade power flow, as a method to mitigate the risk of a thermal overload, or to encourage power flow and relieve stress from parallel transmission routes. The current generation of VSC-based FACTS controllers provides faster control than previously available alternatives, with a more comprehensive control range and lower capital investment. In addition, these technologies require a smaller footprint and produce fewer unwanted grid effects (e.g., sub- or super harmonic order voltages).

The most-important improvement in VSC technology has been the introduction of advanced control techniques not possible with thyristor or current-control converters. These include implementing grid forming control techniques that provide local area benefits and enhance the stability of the bulk power system, paired with an ability to accommodate increased

h D. Sullivan, J. Paramalingam, F. Nakamura, A. Matsuda, D. Yamanaka and T. Tsuchiya, "Application of FACTS Devices for a Dynamic Power System within the USA," 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), Niigata, Japan, 2018, pp. 2329-2334.

asynchronous resource penetration. FACTS technologies like these allow path impedance regulation, facilitating direct control of flow on a line that can regulate congestion and operational challenges, increase stability, and add flexibility to the transmission system.

FACTS implementation entails adding advanced technology to the transmission system for the primary purpose of resolving dynamic issues that require speed and repeatability from the switching devices. However, there are other conventional and common equipment that can effectively enhance power system control, such as:

- Shunt capacitors and/or reactors
- Transformer Load Tap Changers
- Phase shifting transformers
- Synchronous condensers

Identification of the necessary resource to address identified performance issues frequently comes down to classifying the problem. This classification includes determining the most effective solution for system reinforcement. The performance deficiency would be categorized as needing either a shunt or a series connected solution and the correction of the issue would be dependent on if the solution requires a fast or slow response time.
FACTS are known for their ability to provide a rapid and smooth response, as their controls allow them to act in sub-cycle timespans, whereas, the conventional solutions discussed above can require timespans from multiple cycles to multiple seconds to multiple minutes depending on the implemented control method.

1.2 Transmission Switching (TS)

Mandatory reliability standards require building an electric grid that can be protected against worst-case scenarios. As a result, redundancy is common and unavoidable. Current industry practices take advantage of this redundancy in several ways. For instance, switching out lightly loaded lines improves voltage profiles and boosts transfer capability on other higher-voltage assets. These practices treat the grid as a controllable asset and allow the exploitation of further redundancy to overcome transmission congestion, voltage violations, contingencies, and security-constrained optimized dispatch while reducing system losses and manage congestion. The key issue is viewing the grid as a dynamic, dispatchable asset that can be topologically modified as often as needed to increase flexibility and efficiency. However, to achieve these objectives, optimization tools must identify optimal switching scenarios that facilitate power flow control that nevertheless complies with reliability standards.

Figure 2. Substation circuit breaker used to modify system topology.

1.2.1 Variable Line Ratings

Because actual environmental conditions are dynamic, the operational capacity of a power line can be further exploited if real-time environmental information is used to determine its variable rating. Adjusting line ratings to account for environmental variables led to the definition of two primary alternatives to static line ratings (SLRs): ambient adjusted ratings (AARs) and dynamic line ratings (DLRs). As discussed above, FERC has issued an order requiring the implementation of AARs at minimum by the middle of July 2025, barring an approved extension. The order was geared towards making available additional transmission capacity that would otherwise be constrained by assuming that the system would always operate under worst-case environmental conditions—i.e., those used to determine the SLR facility rating. FERC has issued an ANOPR examining the possible configurations of DLR to require implementation within jurisdictional regions. Industry-wide assessments have indicated that many transmission lines can operate safely at 130% of their SLR for 90% of the year[i]. AARs and DLRs are methods to make operational use of these large periods where additional capacity is available on the transmission system by accurately representing that capacity relative to the environmental conditions. Since AAR and DLR predictions can attain more-economical dispatch, they are promising power-flow-control technologies. It should be noted that AARs can present operational risks beyond DLR as they can present a less accurate representation of the operational transmission facility's capacity due to limited visibility of all the variables that influence the thermal loading of the equipment making up the facility. Further information on AARs and DLRs can be found in the Variable Line Rating white paper.

i N. H. Abas, M. Z. A. Ab Kadir, N. Azis, J. Jasni, N. F. Ab Aziz and Z. M. Khurshid, "Optimizing Grid with Dynamic Line Rating of Conductors: A Comprehensive Review," in IEEE Access, vol. 12, pp. 9738-9756, 2024, doi: 10.1109/ACCESS.2024.3352595.

1.2.2 Substation Bus Splitting (SBS)

Circuit breakers, installed in substations, allow for both flexibility in bus configuration and emergency interventions. However, under certain station configurations, the main and transfer substation bus may become electrically disconnected. This configuration could result from breaker mis-operation, malicious cyberattack, or deliberate action. A process known as bus splitting can be used advantageously as a power flow control strategy under these conditions. SBS allows transmission lines, generation, and load to be redistributed through different buses within the same substation to regulate current flow. Substation reconfiguration can be integrated into power flow analyses as a method to mitigate congestion by segregating a common node into multiple nodes in the system, forcing alternate system flows through previously congested common nodes.

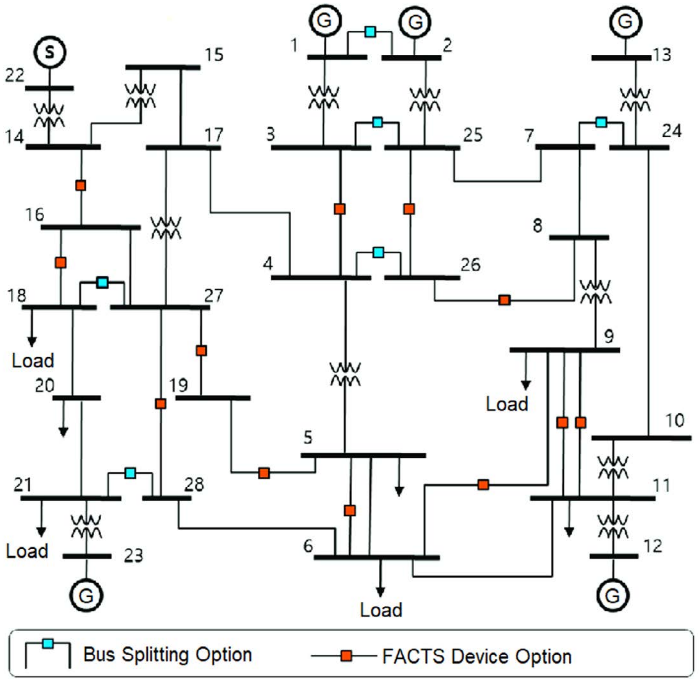

Figure 3. SBS scheme-implementation assessment using 28-bus network by adjusting bus tie breaker status between buses such as bus 18 and bus 27 to regulate current flow between buses at the same station[j].

1.2.3 Network Topology Optimization (NTO)

Reconfiguring the topology of a network is a well-known power flow control strategy that can be used to mitigate congestion, improve transmission capacity, and add flexibility. As network conditions change, it is impossible to attain an optimal network for all circumstances. Transmission providers should expect

j Flores, BenJeMar & Song, Hwachang, "Determining Countermeasures against Fault Currents Using a Decomposition Method Based on Fuzzy Fault Level Constrained Optimal Power Flow," Applied Sciences, 9. 274. 10.3390/app9020274, 2019.

that approaching optimal topology represents a dynamic process, sensitive to transmission constraints, generation dispatch, and demand patterns. These sets can then be used to aid day-ahead scheduling challenges in open markets, improve line-maintenance schedules, and take advantage of seasonal transmission switching.

Using the grid as a controllable asset yields new challenges requiring further research. For instance, although TS can be an effective power flow control mechanism, it can also cause transient stability problems. Thus, further research is needed to determine a safe level of TS. SBS, on the other hand, requires a detailed substation-modeling effort to assess respective flows and ensure breakers are not over dutied. Additionally, the computational challenges of NTO are well recognized in the technical literature; more importantly, while NTO may help attain sets of optimal network configurations, TS, DLRs, and SBS exacerbate the challenges. Research is required to identify which mathematical tools are best suited for attaining optimal power flows (OPFs). Combinations of TS, AARs and/or DLRs, and SBS impact the use of approximations in calculating OPFs. These skew simplifying assumptions like using a direct current network solution rather than a more computationally intense AC network solution, a common practice when calculating OPF. Implementing these practices may also impact the operation of such facilities as protection systems and would require a representation of valid limits that require flexibility to be modified by system operators to protect the system against unintended protection operations. Finally, further research is needed to determine how to optimize the use of FACTS devices along with TS, DLR, SBS, and NTO to make the best use of the grid in its current form.

1.2.4 For More Information

The Idaho National Laboratory (INL) collaborated with POWER Engineers, Inc. (POWER), and Electric Power Research Institute (EPRI) to develop the white papers listed below, covering GET topics. These papers have been developed to provide information and potential use cases for GETs and to show how these can be integrated into study processes to address system-level transmission reliability and capacity expansion issues that cause congestion constraints and slow the interconnection process for new generation resources. These white papers have been broken down into the following topics:

- "Implementation and Operation of Power Flow Control Solutions for Transmission Systems"
- "Cybersecurity Considerations for Dynamic Line Rating Deployment"
- “Shunt Connected Flexible Alternating Current Transmission Systems (FACTS) And Synchronous Condensers”
- “Voltage Optimization”
- “Variable Transmission Line Ratings”

This series aims to provide consolidated information for anyone curious about grid enhancing technologies or beginning to consider any of these technologies for use on their power system.