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Shunt-Connected FACTS and Synchronous Condensers

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SHUNT-CONNECTED FACTS AND SYNCHRONOUS CONDENSERS

In recent years, the electric-transmission system has undergone a significant transformation marked by a greater integration of renewable-energy sources like wind and solar, the phasing out of thermal generation plants, and a concerted effort towards electrifying energy consumption. To keep pace with the integration of renewable-energy sources and the escalating demands of industries and households, it is imperative to expand and modernize the existing power infrastructure. These upgrades are essential to maintain grid stability, enhance power delivery, and boost overall efficiency of the system. However, challenges have emerged with the growing complexity of power grids, particularly in the realms of voltage control, transient stability, and power-quality management.

One resource that addresses these challenges is Flexible AC Transmission Systems (FACTS) that represent both series- and shunt-connected devices. Series-connected devices, such as a fixed series capacitor, thyristor-controlled series capacitor, or static synchronous series compensator, either apply a variable impedance or inject a voltage in series with a transmission line to support the regulation of power flow. Shunt-connected FACTS devices, such as static synchronous compensators (STATCOM) and static var compensators (SVC), provide regulation of transmission-system voltage at the point of connection.

This paper focuses on shunt-connected FACTS devices to address system voltage and nodal-strength and stability issues. For more information on series-connected FACTS devices, please refer to the paper on Flow Control. Synchronous condensers (SYNCON) are another element that can be connected to the system to provide similar support for the regulation of local voltages, as well as a number of additional performance benefits that will be explored later. This paper compares shunt-connected FACTS devices and their performance and capabilities to SYNCONs.

Shunt-connected FACTS and SYNCON devices deliver dynamic vars (reactive power) to improve voltage stability in the transmission system. While FACTS devices commonly operate near zero-var output to preserve their capacity for system disturbances, they can also be used by grid operators to improve steady-state voltage control through continuous reactive-power support. FACTS and SYNCON technologies have emerged as indispensable options in the modern power-system planning toolbox. These resources provide a dynamic solution to address new challenges in the evolving power system, such as voltage stability issues and reduced short-circuit strength. Frequent voltage stability issues include voltage sag, swell, and delayed voltage recovery following system disturbance. Every regional electric grid is required to develop voltage stability requirements to ensure the reliable operation of their grid. Provided in Figure 2 is the voltage recovery criteria for the Western Interconnection. Violations of such voltage stability requirements represent a loss of voltage control in an area which can lead to voltage collapse or load shedding, especially if subsequent unexpected events were to occur while the local voltage is still depressed.

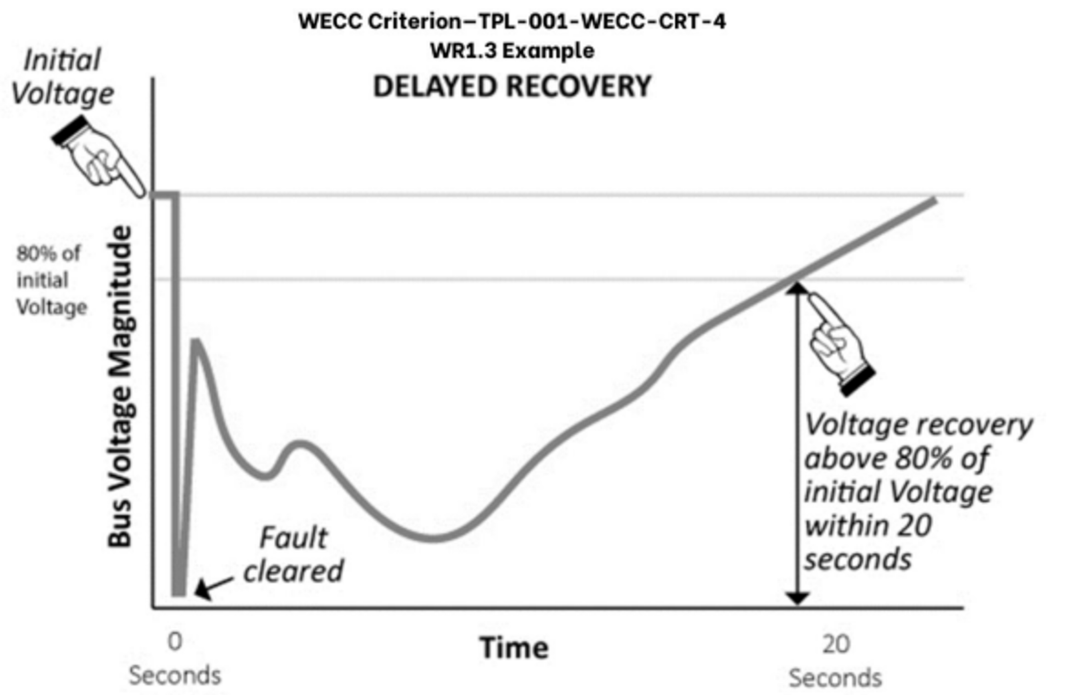

Figure 1. Delayed Recovery

One increasingly common type of voltage stability issue is fault-induced delayed voltage recovery (FIDVR) which is typically caused by a high penetration of induction motors in an area with limited access to dynamic reactive-power support. A key driver of FIDVR phenomena is the scale and performance of household air-conditioner units, such as window units, use of which could increase by more than 8% in the U.S. as average temperatures rise[a]. During a fault, these motors may stall during the low-voltage conditions which causes them to absorb significant reactive power, which works to hold the voltage low and slow voltage recovery. An example of typical FIDVR performance has been provided in Figure 2.

a R. Obringer, R. Nateghi, D. Maia-Silva, S. Mukherjee, et al, "Implications of Increasing Household Air Conditioning Use Across the United States Under a Warming Climate," Earth's Future, 2022.

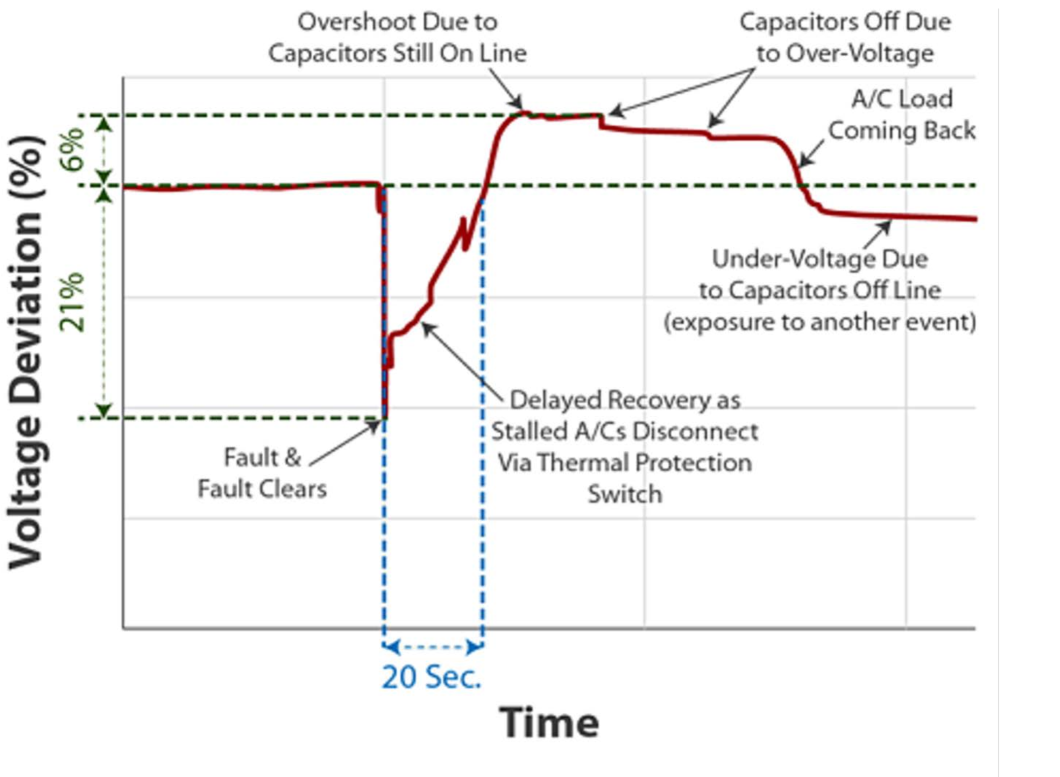

Figure 2. Typical FIDVR-event characteristics in transmission system[b].

A critical period begins once the fault is cleared from the system when the voltage begins to recover and motors attempt to speed back up causing a significant draw of reactive power from the system. This draw of vars can easily exceed what is required during steady-state operating conditions. Without a local source, supplying dynamic reactive power across the system causes a sizeable voltage drop that perpetuates the depressed voltage and can lead to uncontrolled voltage collapse. Dynamic reactive devices ramp var output during the critical recovery period when there is often a high demand for reactive power, and ramp back down once the voltage is recovered. Conventional mechanically switched shunt capacitor banks, while efficient for steady-state voltage support, are less effective for dynamic voltage support.

A FACTS or SYNCON is much more effective at mitigating FIDVR to ensure acceptable power-system dynamic performance and other voltage-stability issues, improvements in power-supply reliability, and reduction of the risk of cascading failures. Voltage stability and the dynamic reactive-power control features offered by shunt-connected FACTS or SYNCON can improve power quality, reduce voltage flicker, harmonics, and other voltage disturbances that damage sensitive equipment and disrupt operations. With the increasing penetration

b Consortium for Electric Reliability Technology Solutions, "Fault-Induced Delayed Voltage Recovery (FIDVR)," https://certs.lbl.gov/initiatives/fidvr.html.

of variable energy sources, FACTS and SYNCON also help manage the intermittent nature of renewables by stabilizing the grid and enabling smoother power transfer as these resources unexpectedly ramp their power delivery. Shunt- and series-connected FACTS also help to optimize power flow and reducing transmission losses (Figure 3).

As previously mentioned, shunt-connected FACTS typically consist of two technologies, SVC and STATCOM. Throughout the 2010s, the STATCOM largely displaced the SVC due to performance improvements, smaller footprint, reduced equipment and complexities, and expanded capabilities. The SVC is based on thyristor technology with an ability to control shunt capacitors and reactors. Fundamentally, an SVC operates to absorb or supply reactive power to regulate transmission system voltages. SVC current output is dependent on the local voltage, similar to shunt capacitors, where the var output varies with the square of the voltage. STATCOM current output is independent of the voltage, where the var output then varies linearly with the voltage. This difference in performance is significant when supporting the system during undervoltage and FIDVR events. Both technologies are capable of a continuously variable response capability; however, as opposed to STATCOMs, SVCs designed for continuously variable control require fixed filters to meet harmonic-performance requirements. SVCs controlled in var steps eliminate the need for fixed filters.

STATCOMs are a form of shunt-compensation devices that provide reactive-power support, voltage regulation, and the ability to increase short-circuit strength with grid-forming controls, as discussed below. STATCOMs function by counteracting voltage fluctuations and disturbances, ensuring a stable and consistent supply of electrical energy to consumers. They are particularly effective in enhancing power quality and system resilience. Another performance improvement that distinguishes STATCOMs from SVCs is the recent incorporation of grid-forming (GFM) control strategies that allow for the mitigation of weak-grid issues[c], as well as additional system-performance improvements. STATCOMs that incorporate energy storage are also being installed, intended to inject real power that effectively acts like inertia and can support a system's resilience during a disturbance. Previously synchronous condensers were the only solution that provided inertia and short-circuit current.

c Refer to https://inl.gov/content/uploads/2024/03/Voltage-Optimization.pdf.

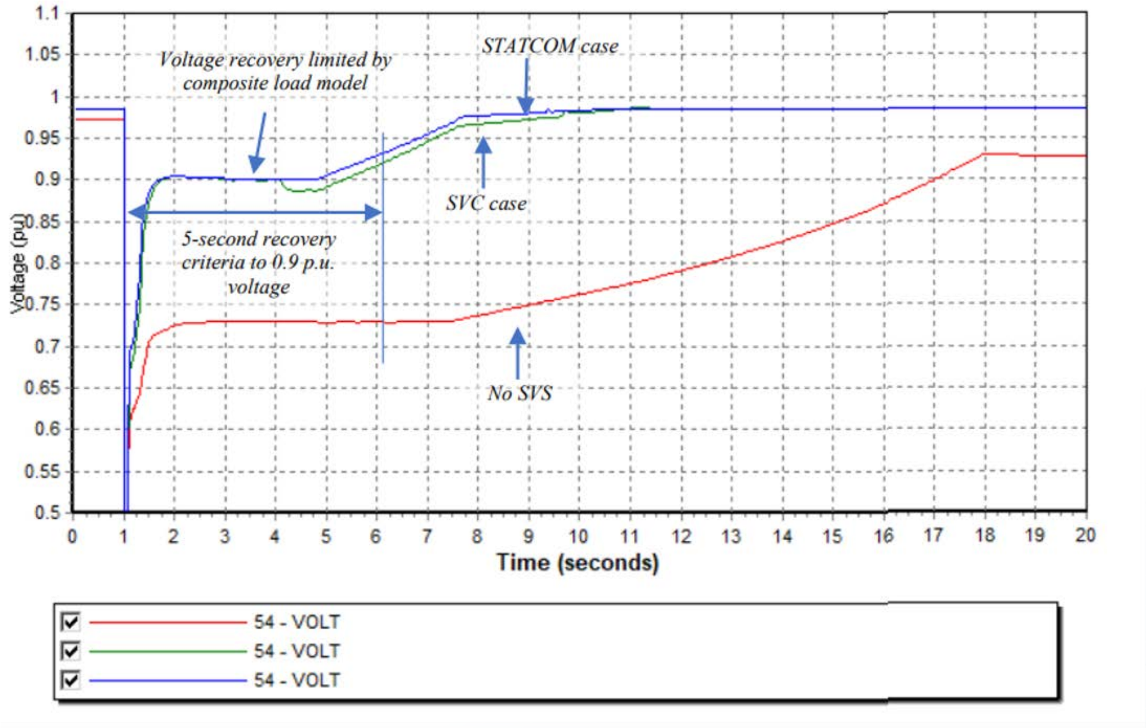

Figure 3. Comparative voltage response to mitigate voltage violation using SVC and STATCOM.

The example voltage response (Figure 3) represents a violation of voltage-recovery criteria for a system within the United States. This FIDVR violation was caused by the interconnection of a large data center load represented dynamically as a composite-load model (CMLD). These load characteristics have a strong influence on these recovery characteristics. In this instance, the SVC and STATCOM provide similar performance and successfully mitigate the voltage-recovery violation. The performance or voltage recovery would vary for a given application of these resources. The difference for this solution would be in comparing the technologies on their costs, losses, maintenance, and footprint requirements. A general technology comparison has been included as Table 1.

Unlike SVCs or STATCOMs, SYNCONs are synchronous rotating machines, often similar to synchronous generators, but are not connected to a prime mover; rather, their rotor is allowed to spin freely. These devices have a direct current-excitation system that works to regulate the reactive power developed for use in power-factor correction or voltage control under normal system-operating conditions. Previous SYNCONs largely consisted of converted generators, but modern SYNCONs can be designed to prioritize specific performance such as maximizing inertia, fault-current, and reactive-power contribution, etc. The implementation of SYNCONs as system solutions needs to be balanced against their increased losses and operations and maintenance costs.

The approach of converting generators to SYNCONs incorporates some increased risks as older generators typically have outdated technologies and aging components that require maintenance and can be difficult to replace. Retrofit considerations should be performed on a case-by-case basis, with a detailed assessment of the relative benefit compared to alternatives. This should include strong engagement with the original equipment manufacturer. At times, retrofitting may prove to be prohibitively expensive if a single component is found to have excessively high losses, fatigue, or damage for its operational life to be extended. In this case a new-build SYNCON would be considered.

In summary, emerging FACTS technologies and new implementations of SYNCONs have been shown to provide key services to assist the regulation of the power system as it undergoes rapid changes in historical resource mixes. The following table provides a comparison of the various technologies on several factors, depending on their capabilities. This table has been developed treating the requirements for an SVC as the reference for the other technologies.

	Parameter	Static Var Compensator	STATCOM	Synchronous Condenser
1	Typical Transmission System Applications	Regulate Voltage	Regulate Voltage	Regulate Voltage
		Improve Transient Stability	Improve Transient Stability	Improve Transient Stability
		Improve Fault Recovery	Improve Fault Recovery	Inertia, Short Circuit Current
		Increase Power Transfer Capacity	Increase Power Transfer Capacity	Increase Power Transfer Capacity
2	Increases System Short Circuit MVA	No	No (Yes with Grid Forming design)	Yes
3	Increases System Inertia	No	No for conventional design Yes with Grid Forming and energy storage design	Yes
4	Typical Speed of Response	2 to 3 cycles	1.5 to 2 cycles	20 to 30 cycles
5	Approximate Reactive Power Capability	As Required - Flexible Custom Design	100% inductive & 100% capacitive	50% to 60% inductive & 100% capacitive
6	Ability to support voltage	Decreases with V2	Decreases with V	Decreases with V
7	Losses—No Load (of Full Capacitive Output)	~ 0.20 % to 0.30%	~ 0.10 % to 0.15%	~ 1%
8	Losses—Full Load (of Full Capacitive Output)	~ 0.8%	~ 1.0 %	~ 3%
9	Typical Operating Voltage	10 kV to 40 kV	20 kV to 70 kV	13.8 kV to 25 kV
10	Harmonic Filters Required	Yes	Normally No	No
11	Minimum SCMVA	3 pu	1 pu, less with grid forming	Moderate
12	Installation Space Requirements	100%	60%	60% to 70%
13	Operating Maintenance Costs	Low	Low	Moderate

Table 1. Comparison of SVC, STATCOM, and SYNCON.