EPRI



2025 White Paper

Advanced Power Flow Controllers Status, Applications, and Opportunities

A GET SET White Paper



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FOREWORD

What is GET SET?

Energy companies are seeking all options for increasing delivery capacity to support energy transition objectives and large demand increases from artificial intelligence (AI) and manufacturing growth. EPRI's GET SET (Grid-Enhancing Technologies for a Smart Energy Transition) initiative aims to support the deployment of a subset of technologies to respond to the rapid load growth, changing generation mix, and extreme weather that energy companies are facing today. These solutions can potentially maximize the capacity of existing assets now while working to build new capacity in the long term. For example, the differing speed of construction of new loads compared to transmission is one driver for increased grid congestion. The resultant increased electrical loading can push transmission lines to or beyond their safe operating limits. While deploying grid-enhancing technologies (GETs) is seen as a potential method to increase capacity from transmission lines and satisfy load growth, deployments must also ensure system stability, asset health, and public safety are maintained.

The GET SET initiative is committed to assimilating and disseminating existing GETs knowledge to support utilities in assessing and deploying GET now, as well as leveraging those deployments and additional research to answer remaining questions and provide the tools that utilities need to evaluate and deploy more broadly.

GET SET White Paper Series

The GET SET white paper series is a collection of papers that describe four promising GET: Dynamic Line Ratings (DLR), Advanced Conductors, Advanced Power Flow Controllers (APFC), and Transmission Topology Optimization (TTO). This white paper aims to document the current state of the science regarding APFCs and their potential applications and identify opportunities for greater research and collaboration.

INTRODUCTION

Advanced power flow control (APFC) technologies are power electronic-based devices that can actively change the way power flows through the transmission system without making changes to generator dispatch or the topology of the network. In that way, these devices can divert power flow from congested lines to other circuits with spare capacity, making more efficient use of the transmission assets.

APFCs have notable advantages over traditional methods for power flow control such as phase-shifting transformers and series reactors. They can be dynamically controlled in a very fast manner, thus responding to system control needs without delays. Additionally, in certain conditions, they can provide dynamic services such as transient stability improvement and oscillation damping. Because they do not rely on electromechanical components, they have smooth and continuous control with no limitations on the number of operations. Some APFC devices are designed to be modular and voltage-agnostic, meaning that more APFC devices can be added to existing deployments over time, or devices can be relocated to an alternate site as network needs change.

Recent directives from the Federal Energy Regulatory Commission (FERC), including FERC Order 2023 and Order 1920, highlight the significance attributed to APFCs in realizing the United States' renewable energy objectives, particularly in the intervening years for significant development of new transmission. With the advancement of this technology, APFCs are anticipated to become vital components of transmission infrastructure.

While APFCs are commercially available and deployed in various systems globally, not many transmission utilities have first-hand experience in their service territory. Indeed, one of the most significant barriers to the deployment of APFCs, especially in the United States, has been the lack of utility understanding of how to consider and operate this technology. Therefore, to catalyze broad deployment, it is essential to increase transmission planners' and engineers' understanding of the technology capabilities through a comprehensive characterization of the performance, benefits, deployment, and operational considerations, and by providing tools and processes to utilities to plan, acquire, install, operate, and maintain these devices.

STATE OF THE TECHNOLOGY

A select group of technology providers has achieved a level of readiness that will allow the commercial deployment of APFC.

SmartValve™ Device

Smart Wires Inc.[1] offers the SmartValve™, a modular static synchronous series compensator (M-SSSC). This device injects a leading or lagging voltage in quadrature with the line current, functioning similarly to a series capacitor or reactor. Unlike conventional series capacitors or reactors, the SmartValve can inject the voltage independently of the line current, thus increasing the effective reactance injection when operated below the rated current. SmartValve solutions are connected in series with the utility network, operate at line potential, and have no electrical connection to the ground.

Designed to be modular and voltage-agnostic, SmartValve devices can be easily added to existing deployments or relocated as network needs change. This flexibility allows installations to meet specific substation or site restrictions. Multiple devices per electrical phase ensure no single point of failure; if a device fails, it is automatically bypassed, and the rest remain operational. SmartValve employs voltage-sourced converter (VSC) technology using insulated-gate bipolar transistors (IGBTs) arranged in an H-bridge to inject a voltage directly into the network facility to achieve the desired reactance.

Smart Wires uses a proprietary end-to-end communication and control (E2E) system for real-time monitoring and control of SmartValve devices. The E2E system includes PowerLine Coordinators™, the PowerLine Gateway™, and SmartValve devices. PowerLine Coordinators handle fiber-optic (FO) connections, while the PowerLine Gateway acts as a system controller, supervisory control and data acquisition (SCADA) system gateway, and local historian. The system is redundantly deployed to ensure uninterrupted operations and uses only fiber-optic connections to mitigate cybersecurity risks.

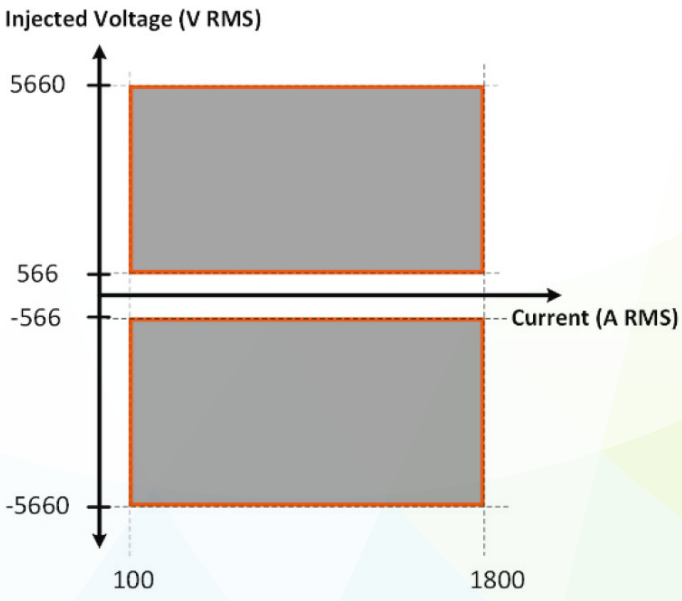
1 www.smartwires.com



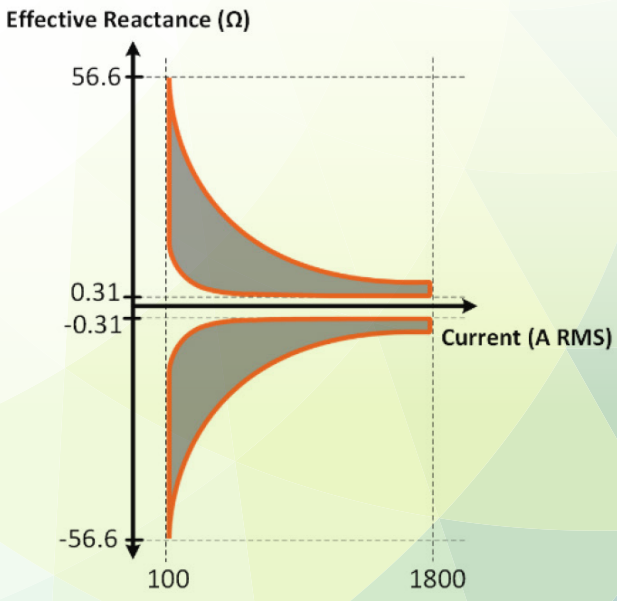
Figure 1. *SmartValve installation in the National Grid transmission system in the UK [Courtesy of Smart Wires Inc.]*

Figure 2 shows the operating range of the SmartValve 10–1800, which provides 10 MVAr of power flow control capability with a maximum continuous current rating of 1800 A RMS and a maximum voltage injection of ±5660 V RMS. There are two available SmartValve models, differentiated by their maximum continuous current rating (1800 A RMS and 3600 A RMS) and corresponding voltage injection capability (±5660 V RMS and ±2830 V RMS). Smart Wires is expected to launch a high current product that can operate on the 4000–4800 A RMS range.

The SmartValve is a single-phase device, so individual units are installed across all three phases. It has an integrated fast-acting bypass for protection and control, which enables injection modes under normal operating conditions and provides fast protective action during line fault conditions. When the bypass senses a line current indicative of a line fault, it automatically fires the fast-acting antiparallel silicon controlled rectifier (SCR) switches, bypassing the SmartValve within 1 millisecond. The bypass can also be closed in steady-state conditions. In that case, the operating mode is called "monitoring mode," as the system operator has directed the SmartValve not to inject voltage, but telemetry information is still sent back via the communication system to the substation.



(a) Voltage operating range



(b) Effective reactance range

Figure 2. *SmartValve operating range*

SmartValve offers advanced control capabilities, allowing operators to adjust the injected voltage independently of the line current to vary the series reactance in real time. Control methods include:

- **Monitoring Mode:** No voltage injection; system is bypassed. Telemetry communication is still active.
- **Fixed Voltage Mode:** Outputs a fixed voltage injection, varying reactance with line current changes.
- **Fixed Reactance Mode:** Emulates a fixed reactance, varying voltage to maintain set reactance.
- **Current Control Automatic Mode:** Regulates line current to maintain it below or equal to a given level.

SmartValve devices have been installed in various power systems in different countries, including the UK, Australia, Canada, Colombia, and the United States. Details are listed below:

- **Pacific Gas and Electric (PG&E) Company:** This pilot aimed to gain operational experience and demonstrate the technology's safe and effective operation on PG&E's transmission system. The project showed that these technologies could reduce line flow and phase imbalance while maintaining high availability and reliability, with minimal impact on primary protection systems [1].
- **EirGrid:** In Ireland, three SmartValve units were installed on a 110-kV line for a pilot project. Over a year, EirGrid tested the technology's availability, reliability, power flow control capability, communication, performance under faults, and structural integrity during harsh weather. The results confirmed that SmartValve performed as expected [2].
- **New York State:**
  - **Pilot:** Central Hudson Gas & Electric installed three SmartValve devices and corresponding bypass circuitry on a 115 kV line. EPRI observed the pilot to evaluate the technology, identify improvements, and suggest further analysis [3].
  - **Large Scale:** The Leeds-Hurley Avenue project expanded the pilot with a large-scale deployment (15 SmartValves) at 345 kV, unlocking over 185 MW of capacity on the existing grid [4].
- **Greek Transmission System:** In collaboration with the Greek Independent Power Transmission Operator (IPTO), Smart Wires installed six modular power flow control devices in a mobile container unit. This project demonstrated the ability to redirect power flows, increase network transfer capacity, and protect against unforeseen line outages. The unit was later moved to Bulgaria, showcasing the technology's mobility and redeployability [5, 6].
- **National Grid Electricity Transmission (NGET):** In early 2021, National Grid installed 45 SmartValves across five circuits at three substations in northern England, unlocking 1.5 GW of network capacity [7]. In response to the increased demand for power flow control following the closure of a nearby power station, two deployments were expanded with additional SmartValve devices in 2022/2023, unlocking an extra 500 MW of capacity.
- **Colombia:**
  - **Termocandelaria Project:** SmartValves were installed on two 220-kV circuits to control power flows, enabling an additional 252 MW of generation from the Termocandelaria plant [8].
  - **Aburrá Valley Project:** Empresas Publicas de Medellin (EPM) used SmartValve devices at two substations to alleviate grid congestion, unlocking 400 MW of capacity for distributed hydro and solar generation [9].
  - **CO-COST Project:** ISA TRANSELCA deployed SmartValves on two circuits to address grid congestion, unlocking 300 MW of capacity for renewable energy. Additional projects are planned to further enhance capacity [10].
- **Australia:** In 2022, Transgrid deployed 15 SmartValves across two 330-kV circuits at the Stockdill and Yass substations. This increased grid capacity by 170 MW on the Victoria-NSW Interconnector, saving approximately AUD $268M in dispatch and capital costs [11].



Figure 3. *(a) ISA TRANSELCA (b) NGET (c) Central Hudson (d) Transgrid's Stockdill Substation [Courtesy of Smart Wires Inc.]*

INGEGRID™ PFLOW

INGETEAM[2] is the technology provider for a transformer-coupled static synchronous series compensator (SSSC). This device is connected in series with the transmission line, imposing a controlled impedance (±X) at the power frequency. It features a voltage source converter connected in series to the transmission line through a transformer. The SSSC injects a series voltage that leads or lags the line current by 90 degrees, effectively mimicking controllable inductive or capacitive reactance at the power frequency. This allows for the modification of the equivalent line impedance. The control modes of the SSSC include power flow control, power flow threshold window (limit or increase), and series impedance control, which help to limit line overload or attract power flow from other overloaded lines.

The first demonstration of this device took place in Europe, entering operation in 2015 at the 220-kV Torres del Segre substation. It has been an integral part of grid operations for the grid operator Red Eléctrica de España (REE) ever since. High wind and hydro energy production injected into the grid caused the 220-kV high-voltage lines around Torres del Segre in Spain to become overloaded. To relieve congestion, the system operator was forced to curtail renewable energy production. An SSSC installation was chosen as a technological solution to alleviate this congestion. The active dispatching of power flows led to an increase in renewable energy integration. The device is also helpful in ensuring a reliable operation during N-1 and post-fault contingency situations.

Since the pilot demonstration, the technology has undergone upgrades at the component, topology, architecture, and control levels. For example, the new design doubles the output voltage to provide a 6.6-kV (line-to-line RMS) output voltage at the LV windings of the coupling transformer and 10-MVA output power bricks with a modular architecture, capable of providing a combined VA rating of over 100 MVAr

2 https://www.ingeteam.com/en-us/home.aspx

on a single-transformer arrangement. Higher VAr ratings can be achieved by adding further units in series, by combining them with passive compensation, or even by the development of higher VA-rated building blocks (consult with the manufacturer). The use of a coupling transformer allows for optimizing the converter's MVA and current rating, capable of working on HV lines of a few thousand-amp rating; it limits the line's fault current level; facilitates access and maintenance, providing static compensation even when the voltage-source converter (VSC) is standstill; and decouples transients between the VSC and the power line. New control functionalities include negative sequence control, subsynchronous resonance damping (SSRD), and power oscillation damping (POD). The SSSC can play a crucial role in maintaining power system stability and achieving better damping of inter-area oscillation modes through a POD controller, which is typically designed as an additional high-level control loop. This upgraded version is now modular, scalable, and market ready, although it has yet to be incorporated or installed in an operating power grid.

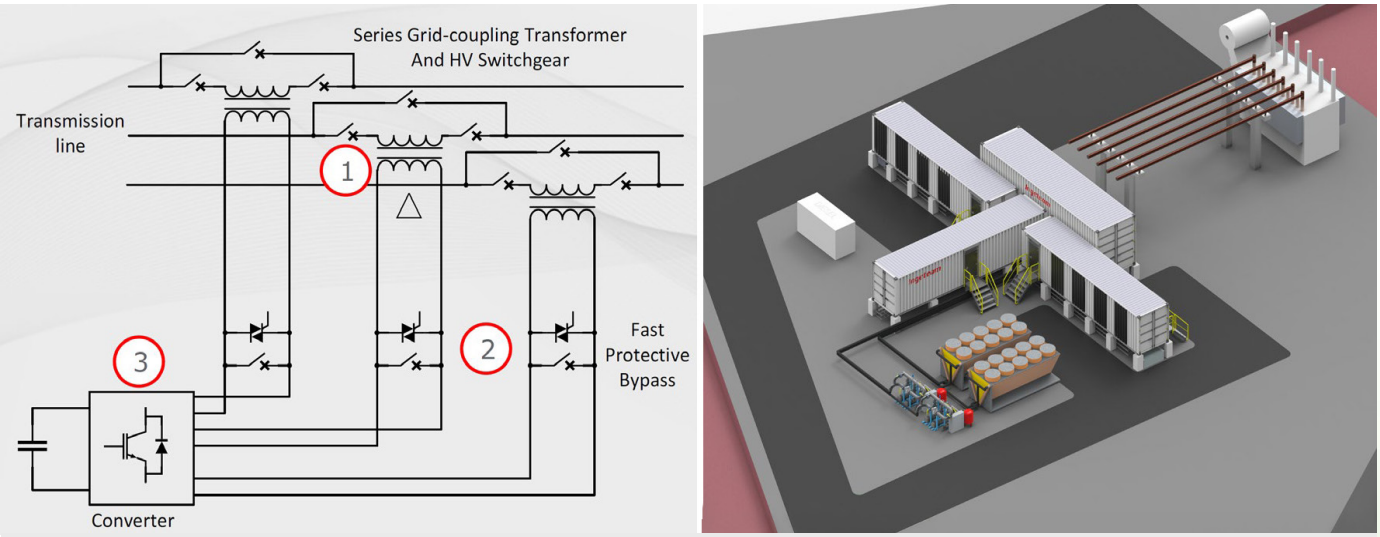


Figure 4. *SSSC schematics, (1) grid-coupling transformer, (2) switchgear and bypass, (3) VSC converters [Courtesy of INGETEAM]*

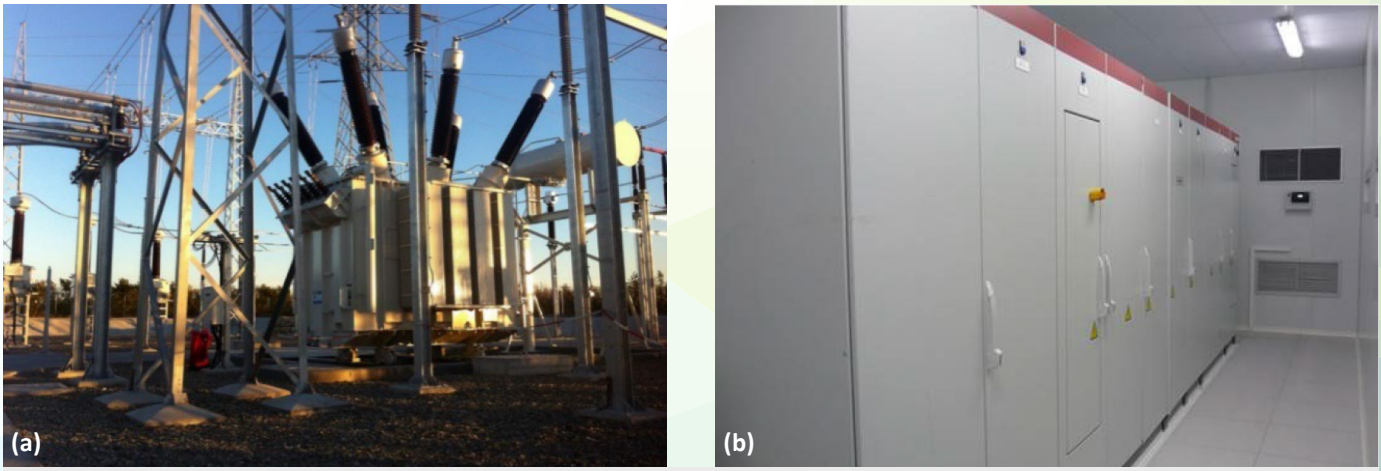


Figure 5. *(a) SSSC at Torres de Segre (b) VSC controllers in-house at Torres de Segre [Courtesy of INGETEAM]*

UPFC PLUS

Siemens Energy[3] commercializes the UPFC PLUS®, a unified power flow controller (UPFC) device that utilizes modular multilevel IGBT voltage-sourced converter technology. These devices can be designed for system voltages ranging from 200 kV to 500 kV and are tailored for specific purposes, with design and operational characteristics varying significantly between installations.

The UPFC PLUS® features fast reaction times and can manage both series and parallel compensation to maintain lines within the N-1 criterion, ensuring continuous electricity flow. It balances load flow in the AC grid, rapidly bypasses overloaded line sections, provides reactive power and dynamic voltage control, and maximizes asset utilization without the need for safety margins.

The UPFC is configured with two voltage sources: one in parallel to control voltage and one in series connected to the AC line. This setup allows for reactive power compensation, voltage control, and active power load flow control in a single unit. The system comprises four main components:

1. **Converter Arrangement:** Configured as a symmetrical monopole, back-to-back with the DC link. Although similar to a high-voltage direct current (HVDC) system installation, it serves a different purpose and has distinct controls.
2. **Modular Multilevel IGBT Voltage-Sourced Converter (VSC):** Achieves the required voltage level.
3. **Series Transformer:** Injects voltage into the transmission line to either reduce or increase current flow through the system.
4. **Shunt Transformer:** Controls voltage and infeed reactive power, ensuring the voltage remains within ±10% limits.

There may be existing installations, but no public records have been found so far.

PCS-8200 UPFC

NR Electric Co.[4] commercializes the device PCS-8200 UPFC (Power Conversion System 8200 Unified Power Flow Controller) [12]. It is a type of flexible AC transmission system (FACTS) device. It regulates power flow, controls line active and reactive power, and enhances transmission capacity in steady-state conditions. In transient states, it provides fast-acting reactive power compensation and voltage support and improves system voltage stability, damping, and power angle stability.

It is a modular multilevel converter (MMC) to adjust the output voltage phase angle and amplitude of the series transformer. The control functions are categorized into injection voltage regulation, line impedance regulation, phase angle regulation, and combined regulation.

The PCS-8200 system includes several key components. The control and protection system is the core of the UPFC, managing control, monitoring, and protection of all equipment. It supports various operation modes, including UPFC, SSSC, and static synchronous compensator (STATCOM), and ensures smooth start/stop functions. The thyristor bypass switch (TBS), installed at the series transformer's terminal, quickly bypasses the series converter during faults, ensuring AC line stability.

The UPFC can provide steady state and dynamic control of the AC voltage and reactive power on the parallel side, and terminal voltage, phase, impedance, and power flow on the serial side. One notable installation of this technology has been operational since the end of 2017 in Suzhou City, China, and is operated by the Southern Power Grid (SSPG) [13]. It is claimed to be the first to adopt MMC technology. While it has several applications, its primary uses are to provide reactive power support to the SSPG grid and to increase transmission capability in the area.

BENEFITS AND USE CASES

Table 1 presents a concise overview of APFC use cases. It serves as a reference and strategic guide, illustrating how this technology could address a variety of transmission challenges. The table indicates for each application whether a traditional solution[5] could be applied and, in such a case, why an APFC-based solution would be chosen.

3 https://www.siemens-energy.com/global/en/home/products-services/product/upfcplus.html

4 https://nrec.com/en/

5 Traditional solutions may include building new transmission facilities, thermal or voltage upgrades of existing lines and substations, series reactors and capacitors, and reactive power compensators.

Table 1. *APFC use cases*

APPLICATION	APFCS	TRADITIONAL SOLUTIONS*	WHY APFC?
Increase Transmission Capability (Reliability Projects)	☑	☑	APFCs may have lower costs, faster construction time, and expansion flexibility.
Reduce Transmission Congestion	☑	☑	APFCs may have lower costs improving the benefit/cost ratio. Reduced construction time may allow faster realization of benefits.
Mitigation of Unscheduled Flows and Enforcement of Contractual Flows	☑		APFCs have advantages over traditional phase shift transformers: • Reduced maintenance costs related tap changers. • Digital control provides continuous and smooth control.
Short-Term Solution To Temporary Operational Challenges (Construction, Maintenance, Severe Weather Impact)	☑	☑	The ability of rapid deployment and flexibility to relocate the technology.
Adaptive Expansion Solutions	☑		Specifically, M-SSSC-based technologies as they are modular, scalable, and can be redeployed to other different locations.
Improving Oscillation Damping	☑		The ability of dynamic control of transmission line impedance provides a quick response time to oscillation events.
Subsynchronous Resonance (SSR) Immune Series Compensation	☑		APFC, especially M-SSSC, can provide series compensation on transmission lines without creating SSR risk.

Increase Transmission Capability

Transmission system expansions or reinforcements are essential to meet reliability requirements. Identified through the transmission planning process, these expansions aim to achieve optimal, cost-effective solutions. While conventional upgrades like new lines and substations remain the primary means of increasing capacity, APFC technologies offer viable, cost-effective alternatives by maximizing existing infrastructure. In certain cases, APFCs can defer or replace capacity expansion projects required to solve thermal overloads by diverting power flow to circuits with spare capacity. Examples of common transmission reinforcements or upgrades include increased capability of a transmission corridor or transmission interface, increased import capability into a load pocket, and increased export capability of an area with surplus generation. It is noteworthy to emphasize that reliability expansions are those required to ensure that the transmission system is in compliance with all of the applicable reliability requirements, and as such they are to be implemented. In this case, the decision to choose among viable alternatives is based on technical merits and costs.

Reduce Transmission Congestion

Transmission congestion occurs when power flow exceeds the capacity of transmission elements due to scheduled transactions, leading to increased operational costs. In the United States, congestion can add billions of dollars annually, so reducing these costs can save consumers significantly. Traditionally, congestion is mitigated by expanding transmission capacity. Alternatively, APFCs can redirect power flow from congested lines to circuits with extra capacity, allowing more economic resources to provide energy and reducing congestion costs. APFC technologies generally have lower capital costs and shorter installation times compared to transmission expansion, and they face fewer regulatory and jurisdictional challenges.

A few studies have been performed to estimate the potential congestion reduction that can be achieved with APFC and, more generally, with other grid-enhancing technologies. For example, a study by the U.S Department of Energy (DOE) analyzes how GETs could help integrate more renewable generation into the existing transmission infrastructure in the New York area [14]. The study analyzed different op-

tions and used various metrics to evaluate the benefits. In particular, for APFC, the results show a reduction in annual wind and solar generation curtailment of 188 GWh/year. The overall network utilization measured as a percentage of line loading is found to improve from 35% in the interconnection without APFCs to 38–49% depending on the number of devices deployed, which demonstrates how these technologies can help optimize the use of existing transmission assets. Another study by EPRI and ABB demonstrated that power flow controllers (PFCs) can significantly reduce congestion costs, depending on factors like placement, control type (phase angle or impedance), control range, and response during contingencies. The study showed substantial cost savings with a small number of PFCs (13 to 17 locations) on an extensive network like PJM. The study also evaluated corrective control, which allows different settings for different contingencies, optimizing device use. While electronic-based devices with near-instantaneous response can improve post-contingency control, the study found that corrective control added only marginal benefits compared to preventive mode. These results may vary based on the system and PFC locations [15].

In general terms, APFCs would not relieve congestion as much as traditional solutions, but they cost less and may be faster to implement. Hence, the solution's economic performance could be better (benefit/cost ratio, payback period, etc.), and the benefits can start to accrue sooner.

Mitigation of Unscheduled Flows

Unscheduled flows, also known as loop or parallel flows, occur when the actual power flow differs from the contracted flow due to the network's impedance configuration. These flows can overload transmission facilities, causing congestion in neighboring systems and limiting power transactions in unaffected zones [16].

A power flow control device such as a phase-shifting transformer (PST) is effective in mitigating loop flows. A notable example is the Lake Erie Circulation (LEC) flow, which affects IESO, MISO, NYISO, and PJM. Factors like system topology, generation dispatch, and scheduled interchange influence LEC flow, impacting grid reliability and market pricing. Five PSTs installed across the Michigan-Ontario interface have successfully controlled LEC, maintaining flow within a ±200 MW band [16]. In the Western Interconnection, ten PSTs at five locations in New Mexico, Utah, Nevada, and Montana manage loop flows [17]. Europe also uses PSTs extensively to mitigate unscheduled flows, especially with the increased renewable energy integration. For instance, wind generation in northern Germany has caused severe loop flows in Poland and the Czech Republic, prompting the installation of PSTs on their borders with Germany. PSTs on Germany's western borders address loop flow issues with France and the Netherlands [18].

No information on the practical use of other APFC devices to mitigate loop flows is readily available. An EPRI study evaluated various FACTS devices on the Southern Company grid, concluding that impedance-change devices (such as series reactors) are ineffective in blocking loop flows due to the need for considerable compensation [19]. While phase-shifting devices can block steady-state loop flows, they may degrade system performance under contingencies. The fast and dynamic control capabilities of APFC can significantly improve contingency response.

Enforcement of Power Flows

Power flow control devices, in particular PSTs, are widely used in North America to maintain contract power flow on specific transmission paths. For instance, the two 345-kV PSTs at Con Edison's Ramapo Substation facilitate power delivery from PJM to New York by controlling the 500-kV line between Branchburg (PSE&G/PJM) and Ramapo (Con Edison/NYISO) substations. These devices are manually controlled hourly to keep actual flows within target values, with an average flow of 650 MW and a deviation of about 230 MW [20]. Seven other PSTs regulate power flow across the eastern AC ties between NYISO and PJM. The PSTs at Waldwick, Farragut, and Goethals substations help deliver a contracted energy wheel from Ramapo to New York City via the 230-kV network in northern New Jersey, typically transferring 1,000 MW daily with a 100-MW bandwidth [20]. These devices also operate manually throughout the hour.

Some PSTs used to enforce power flow can undergo thousands of tap operations per year. In some cases, a significant increase in the number of tap changes has been observed due to high power flow variability caused by renewable generation. That can lead to excessive mechanical wear and tear of the PST, causing increased maintenance costs and force outages [21]. Power electronic-based devices

like APFC provide more precise and smooth control without tap limitations. A hybrid solution combining APFC with PSTs in tandem has been proposed for managing power flow in grids experiencing a rapid rise in renewable energy integration. In this configuration, the APFC handles finer adjustments in power flows thus reducing mechanical stress on the PST, thereby prolonging their lifespan, decreasing maintenance costs, and improving system reliability. The solution is being implemented in the Vermont Electric Power Company (VELCO) as part of the DOE's Grid Resilience and Innovation Partnership (GRIP) program. This DOE GRIP project, entitled, *Increasing Transmission Capacity to Expand Renewable Energy Integration*, is led by EPRI and VELCO.

Short-Term Solution to Temporary Operational Challenges

Short-term reliability needs often arise during the construction of critical transmission projects due to delays or mismatched lead times. In such cases, mitigation actions are necessary to maintain reliability. For new load interconnections, the mitigation measure might be to delay the connection until the project is in service [22]. However, this is not always feasible, and more burdensome measures like generation redispatch may be required. Short-term reliability issues can also occur during planned outages for maintenance or construction.

APFC devices, which can be quickly deployed, offer a cost-effective solution to these reliability issues. A case study published by CIGRE [23] explores using APFC to alleviate overloads when transmission components are removed for new construction. The study found APFC to be significantly less expensive than dispatching out-of-merit generation. Although this study is specific and not universally applicable, it highlights the potential benefits of APFC solutions. Additionally, redeployable APFC devices can be moved and reused in other areas, reducing the capital cost of mitigation projects. For example, SmartValve devices installed in Greece were later moved to Bulgaria, showcasing the technology's mobility and redeployability [5, 6].

Adaptive Expansion Solutions

Transmission expansion planning encounters various uncertainties, such as demand growth, fuel price and availability, renewable energy generation, environmental requirements and legislation, generation retirement, and new generation investment. To address these uncertainties, transmission expansion flexibility proves to be an effective strategy. It enables the system to adapt or respond with minimal penalties in time, effort, cost, or performance. Modular and redeployable APFCs, like M-SSSCs, offer a highly effective option to enhance expansion flexibility. Unlike conventional assets such as lines and substations, which are inherently lumped solutions, M-SSSCs can be installed gradually as system conditions evolve. Additionally, incorporating flexible assets in the planning process allows for deferring major conventional projects until the necessity for such investments is fully confirmed. In other words, they serve as interim solutions until more information about system evolution becomes available, enabling the development of definitive solutions [15, 24].

Improving Oscillation Damping

Inter-area oscillations frequently occur in interconnected power systems. Traditionally, power system stabilizers have been employed to maintain stability. However, some APFC devices can effectively dampen oscillations and enhance power system security by altering the impedance of transmission lines. The SSSC controller uses auxiliary signals to capture frequency impacts and adjust the impedance of the transmission line, thereby improving the damping of inter-area oscillations. Several control schemes have been proposed in the literature to effectively utilize SSSC-based devices for power oscillation damping [25].

Additionally, integrating these advanced devices into the power system can lead to more robust and resilient grid operations. By dynamically adjusting the system's parameters, these devices help mitigate the adverse effects of oscillations, ensuring a more stable and secure power supply. This approach not only enhances the overall reliability of the power system but also supports the integration of renewable energy sources, which can introduce additional variability and uncertainty into the grid.

Subsynchronous Resonance (SSR) Immune Series Compensation

Series compensation is a well-established technology mainly used to reduce reactance in long transmission corridors, leading to a substantial increase in power transfer capacity and enhancing voltage and angular stability in transmission systems. However, in some cases, conventional series com-

pensation solutions may create subsynchronous resonance (SSR) on the system, which poses a high risk to nearby generating units. SSR is an adverse interaction between the electrical characteristics and the mechanical components of the grid. This phenomenon can happen at one or more frequencies lower than the fundamental system frequency, potentially causing torsional vibrations in the turbine-generator shaft. In severe cases, it can lead to equipment damage and electrical instability.

Unlike conventional series capacitors, M-SSSC does not affect the total effective reactance of the system at subsynchronous frequencies. It has been demonstrated that installation of these devices in series with a transmission line does not have a negative impact on the system stability at subsynchronous level, and the probability of amplified subsynchronous oscillations is negligible, especially for systems exhibiting inductive behavior [26].

In addition to these applications, it is worth noting that these technologies can complement other GETs such as dynamic line rating (DLR) and topology optimization, thereby enhancing grid utilization and accelerating grid development. While APFC technology opens many possibilities to improve transmission system controllability and utilization, various practical implementation and integration aspects need to be addressed for successful deployment and use. The following sections delve into these considerations.

IMPLEMENTATION AND INTEGRATION OF APFC SOLUTIONS

Like any technology, to broadly deploy, utilities need to understand how to characterize, plan, operate, inspect, and maintain the assets. APFCs are a relatively new and evolving technology, and there are currently a relatively small number of APFC deployments. As such, there is no long track record of field experience, use, and planning practice. APFC solutions create opportunities to enhance the utilization of the power system network and solve transmission constraints, but they may also increase the complexity of system operations and the management of critical assets. This section delves into some relevant aspects of the design, integration, and operation of transmission solutions using APFC. These features are essential for planners to make informed decisions about the adoption of the technology, for operation engineers to define specific operation and control procedures, and for design and asset engineers to acquire, inspect, and maintain the installations over the life cycle.

Planning Criteria, Models, and Methodology

Implementation of new technologies starts with a needs assessment, which foresees the technology's use on the grid. Transmission planners usually select the most cost-effective options and those that present manageable technical implementation challenges.

A deep understanding of the technology's physical and operational characteristics, uses, and limitations is essential for planners to design and evaluate APFC solutions and compare them with traditional transmission projects side by side to select the option that best addresses the needs of the transmission system and customers. Planners also need appropriate models, analytics methods and tools, and knowledge of operational practices and procedures to operate and control APFCs effectively and reliably.

A systematic approach, incorporating a comprehensive cost-benefit analysis, is crucial for identifying the optimal locations, sizes, and types of technology for specific applications, ensuring seamless grid integration. Establishing metrics and criteria for technical and economic comparisons with alternative solutions is vital for effective planning. Additionally, the evaluation method should account for and value the unique attributes of APFCs, such as their redeployability, which offers greater adaptability to transmission solutions. It is important to assess the extent to which this feature would influence the decision to prefer APFCs over other potential solutions.

Operation and Control

The operation and control of APFC devices largely depend on the particular application. For instance, in scenarios where a single APFC installation is deployed to mitigate overloads during emergency conditions, a local device monitors the line current and initiates corrective APFC actions until the overload is resolved. Another example of automatic local control involves using APFCs to maintain power flow on a specific transmission line within a predetermined bandwidth. In such cases, the control set point is typically established by the system operator, while

the control actions are executed locally based on real-time measurements. This approach is prevalent in North America, particularly within the Eastern Interconnection, where phase-shifting transformers are employed to maintain contracted power flows over designated transmission paths. When the influence area of an APFC device does not overlap with others, there is no risk of mutual interference or adverse control interactions among them.

In certain applications, multiple APFC devices must be coordinated to manage power flow across a wider system area, mitigating line overloads under specific operating and fault conditions. This necessitates a centralized control system to coordinate the APFC operating setpoints, considering the self and mutual power flow sensitivities of each APFC, and to dispatch control commands to all devices. Implementing such a centralized control scheme within the control center and integrating it with existing controls would increase operational complexity.

Consequently, system planners and operational engineers express valid concerns regarding the added complexity in system planning and operation due to APFC solutions. The lack of detailed information and industry experience may hinder the widespread adoption of this technology, particularly in cases requiring coordinated control of multiple APFCs. Therefore, it is imperative to develop strategies and approaches for controlling and operating multiple APFCs within a meshed power network to manage wide-area power flows effectively, minimizing reliability risk. Besides, operation procedures need to be developed for controlling the APFC devices in emergency or abnormal system conditions, and to mitigate the impact of potential AFPC control scheme misoperation or failure.

Technology Performance, Acquisition, and Management

As previously mentioned, the industry has limited experience with the implementation of APFC devices in power systems. Currently, there are no industrywide specifications or standards for APFCs. Additionally, established practices and guidelines for inspecting, maintaining, and assessing these assets over time—such as life expectancy, replacement strategies, and end-of-life removal/disposal—are lacking.

Developing a comprehensive set of technical specifications with minimum performance requirements, along with guidelines for the operation and maintenance of APFC devices, is crucial. This will enable transmission companies to confidently acquire and integrate these technologies into their systems.

Furthermore, it is essential for transmission companies considering the adoption of APFC technology to have a detailed characterization of its technical and economic performance over time. This includes assessing the reliability and availability of the equipment, validating its accuracy, and confirming the intended outcomes (while identifying any potential unintended outcomes) across various operating conditions.

EPRI COLLABORATIVE RESEARCH TO ADDRESS THE NEEDS

The lack of knowledge in the areas described above hinders the wider adoption of the technology, precluding transmission utilities and energy users from the multiple benefits that these devices may bring. EPRI has been performing research and development (R&D) in this area through projects under the annual research portfolio, numerous applications and case studies, and in collaboration with other research entities.

Planning and Evaluation

As described before, to design and evaluate transmission solutions that combine in an effective manner, the capability of various transmission technologies, proper analytical methods, and tools for optimization and simulation analysis are needed. EPRI has developed a software tool called CPLANET that helps identify the most cost-effective solutions for mitigating thermal overloads in a power system over a range of operating scenarios. Figure 6 is an overview of the software's overall architecture, showing the input options and outputs. The optimal solution is determined from a set of candidate projects, which may include a combination of advanced power flow controllers like M-SSSC, traditional solutions such as new or upgraded transmission lines and substations, and energy storage devices like batteries. CPLANET uses a mixed-integer optimization approach with DC power flow representation of the transmission network. A linear cost function is used to represent the cost of the

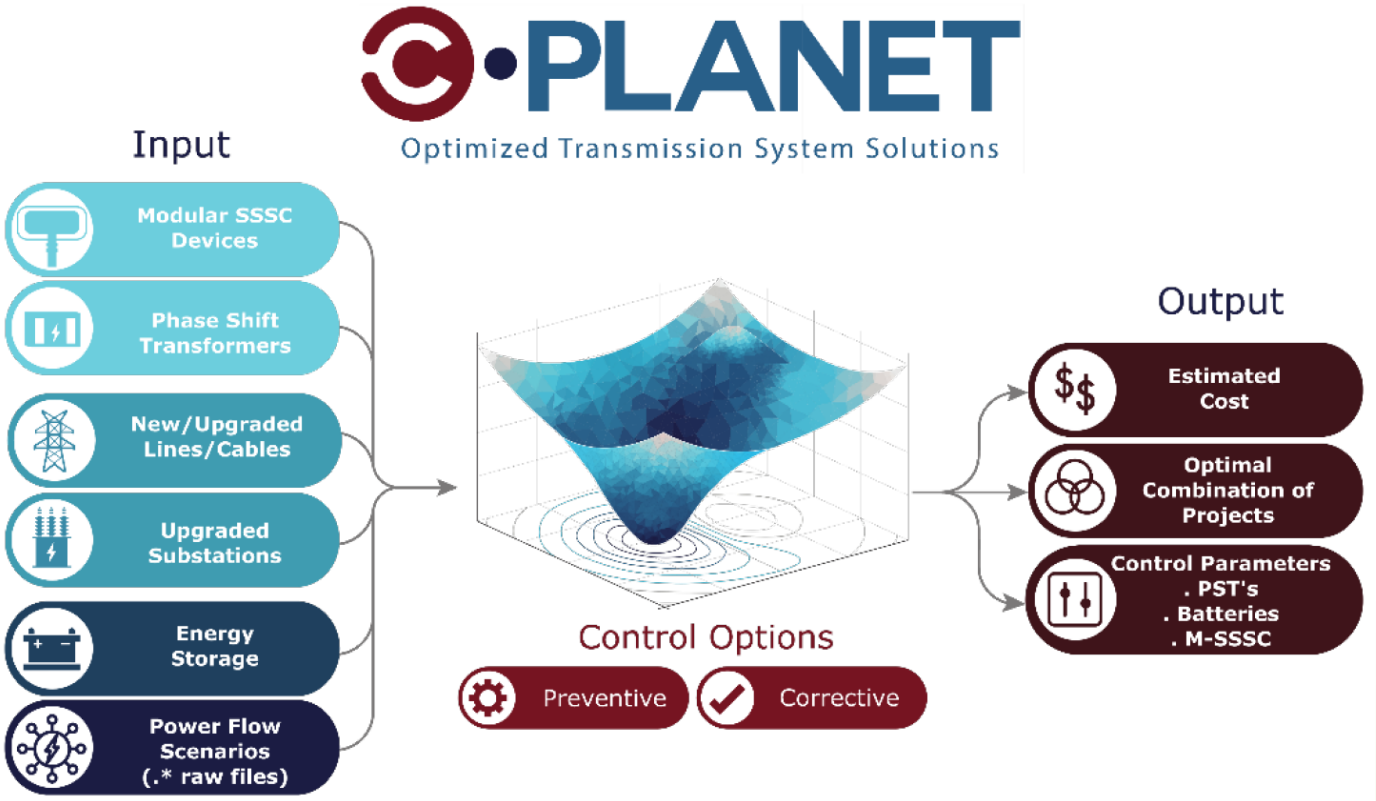


Figure 6. *CPLANET architecture overview [28]*

devices as a function of the maximum control capability, measured by the maximum series voltage magnitude that a set of devices can inject, and the MVA rating. The cost function also includes a constant factor representing a generic fixed for each installation site. The optimization results provide the location of M-SSSC installations, the number of devices at each of the resulting sites, and the total investment cost for each site. A detailed description of the mathematical formulation and software capability can be found in reference [27].

CPLANET software has been extensively utilized in various case studies involving transmission utilities. Below are some examples of these applications:

- **Great River Energy:** Identify the location and capacity of energy storage devices to solve power flow issues
- **Southwest Power Pool:** Analyze the use of power flow controllers to replace/defer transmission investment
- **KEPCO:** Identify the location and capacity of phase-shifting transformers in Seoul metropolitan area
- **PGE:** Analysis of alternative transmission technologies and battery systems
- **FirstEnergy:** Evaluation of M-SSSC alternatives to solve transmission constraints
- **New York ISO:** Analyze the use of advanced power flow controllers (M-SSSC devices) to mitigate thermal overloads in future power flow scenarios
- **EirGrid Group:** Identify a combination of options (GET + traditional expansion) to increase transmission capacity from a large generation area

It is important to note that this tool is designed to identify the optimal location and size of devices to be installed in the system to mitigate overloads in the specified scenarios. The optimization process yields a preliminary solution, which serves as a starting point. Subsequent studies are required to refine this solution and establish the technical specifications to be provided to the manufacturer. The development of the control scheme and real-time operational procedures for the devices will occur in later stages of the overall solution design process. The primary advantage of this tool is its ability to enable planners to select the most cost-effective options from a vast array of possibilities. Designing optimal solutions without a robust tool like CPLANET is exceedingly challenging.

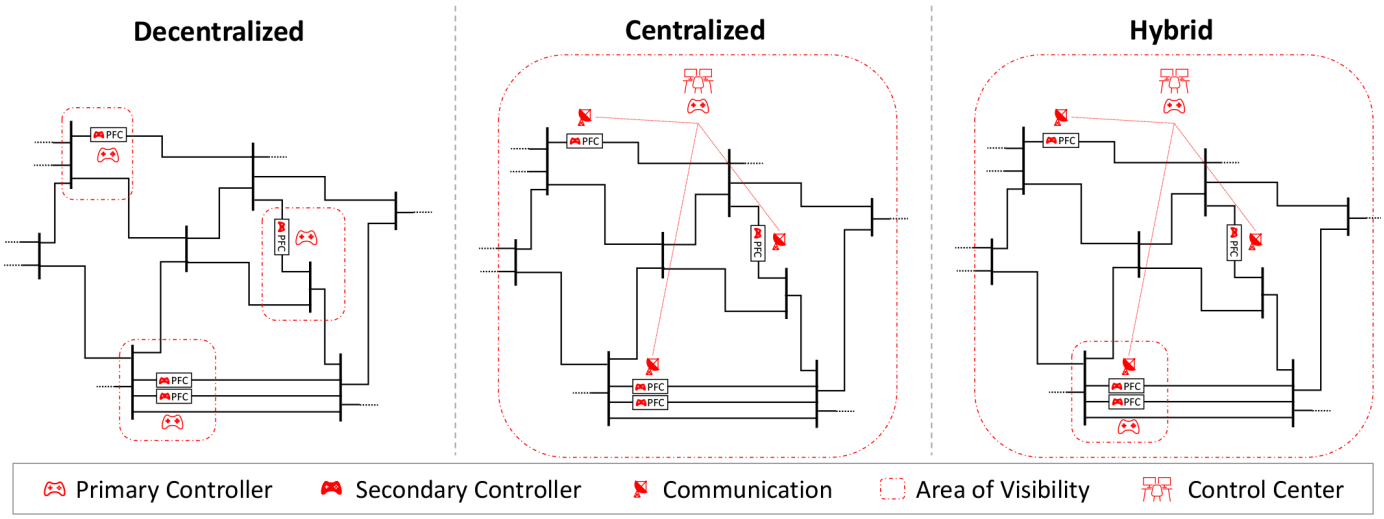


Figure 7. *Qualitative illustration of the difference between decentralized, centralized, and hybrid controllers*

Technology Assessment

SmartValve power flow controllers include complex power and control electronics installed in harsh environments. Environmental conditions include both high electric and magnetic fields, hot and cold temperatures as well as a range of humidity, precipitation, and mechanical conditions. EPRI is in the process of developing test facilities to address many of these challenges to increase the confidence with which technologies can be deployed. Two test setups are in the process of construction at EPRI laboratories:

- **Representative APFC Device Thermal Cycling Test:** A series of tests performed on a representative device that includes power electronics, control, and thermal management systems for an APFC converter and bypass hardware. The test intends to stress the individual components of the APFC devices, especially PCB assemblies, to better understand their reliability and long-term performance by thermal cycling over a range of temperatures and humidity levels while being energized and in injection mode. Figure 8 shows the test setup of the converter in the environmental chamber before testing began.
- **Full-Scale Accelerated Aging Test:** A full-scale test of an APFC device at EPRI's Lenox, MA, laboratory is in development that will naturally age an APFC device in an outdoor environment with additional artificial wetting. The tests that are planned include fully energized at HV during monitoring mode, high current in full injection mode, and performing stress testing including impulse tests.

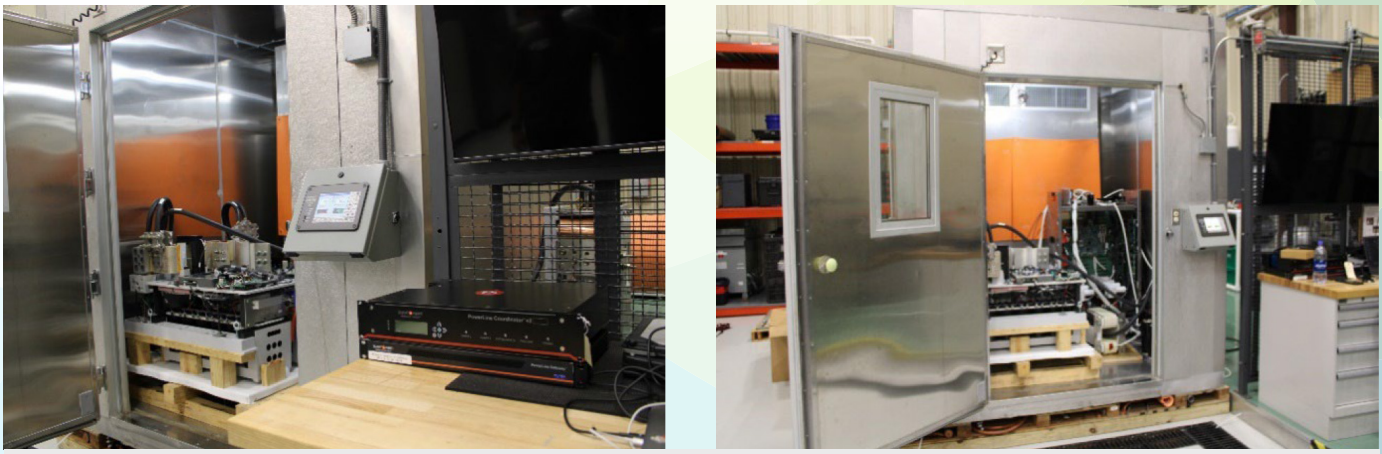


Figure 8. *Representative device test setup at EPRI's Charlotte, NC, laboratory*

The results of these tests are expected to provide valuable learnings and findings to help the electric companies understand the long-term performance and reliability of the APFC devices and installations.

Accelerating Research and Development Through the GET SET Initiative

Recognizing these opportunities for advancement, EPRI's Grid-Enhancing Technologies for a Smart Energy Transition (GET SET) Initiative aims to execute and share results of priority research topics that can accelerate the deployment of GETs and de-risk their deployment and operation. In particular, for APFC, the work includes:

- **Full-scale laboratory testing and development of a guidebook** on APFCs that documents technology evaluation, use cases, installation, maintenance and operation of the devices.
- **An APFC Guidebook and Functional Specifications:** Reference material that documents APFC principles, technologies, installation, inspection, maintenance, life-cycle characteristics, and functional specifications.
- **A planning framework to integrate GETs in the transmission system planning process:** This framework aims to help utilities understand optimal transmission investments, considering whether to defer, replace, or combine traditional expansions with GETs.
- **Guidelines for System Operators:** This document will outline practical guidelines for system operators and operation engineers to maximize GETs' benefits under different operating conditions while reducing potential risks of failure, misoperation, or performance deficiencies. It will include considerations for controlling and operating multiple APFCs.

In addition, EPRI coordinates and supports the APFC Users Group, which is intended to share their experiences related to installation, maintenance and performance of APFC installations to improve the operation of the entire fleet and inform future owners/operators. The user group brings together members who have deployed or are in the process of deploying APFC devices.

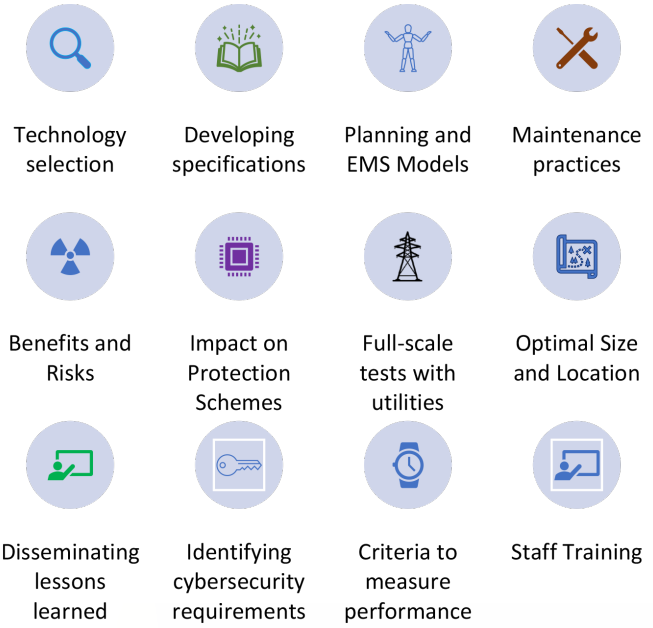


Figure 9. *Objectives of EPRI's GET SET Initiative and APFC Users Group*

The accomplishment of these activities would help develop a thorough understanding of the technology and its uses and will furnish planners and engineers with tools, processes, and technical knowledge to design, implement, and operate cost-effective and dependable APFC-based solutions for transmission systems.

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