GET SET
Grid-Enhancing Technologies for a Smart Energy Transition

Advanced Power Flow Control (APFC)

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 U.S., 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 have achieved a level of readiness that paves the way for commercial deployment of APFC. One such technology provider is Smart Wires Inc.[1] They manufacture the SmartValve™ device, which is a modular static synchronous series compensator (M-SSSC) that injects a leading or lagging voltage in quadrature with the line current, providing the functionality of a series capacitor or series reactor, respectively. 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. Smart Wires's M-SSSCs are modular and scalable; they can be scaled up or down based on project needs. Solutions can be deployed in flexible ways throughout a substation or distributed across multiple substations on the same circuit

1 www.smartwires.com

as needed. SmartValve™ devices have been installed in various power systems in different countries including the UK, Australia, Canada, Colombia, and the U.S.

Figure 1. *SmartValve™ installation in the National Grid transmission system in the UK (Courtesy of Smart Wires Inc.)*

Other technology providers offer a new generation of series FACTS devices that may qualify as APFC. SIEMENS Energy for example commercializes under the brand name UPFC PLUS®,[2] a unified power flow controller (UPFC) device that uses modular multilevel IGBT voltage sourced converter technology. It can be built for system voltages ranging from 200 kV to 500 kV. These devices are tailor designed and built for a specific purpose, and their design and operational characteristics can significantly differ from one installation to another.

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.

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.

2 UPFC PLUS (siemens-energy.com)

Table 1. *Overview of APFC use cases*

APPLICATION	DESCRIPTION
Congestion Reduction	APFCs can redirect power flow from overloaded lines to alternate circuits, effectively reducing congestion costs.
Operational Resilience	They offer dynamic solutions for managing contingency events during grid operations.
System Stress Alleviation	By redistributing power flows, APFCs optimize the use of existing infrastructure, thereby minimizing system stress.
Mitigation of Unscheduled flows	APFCs address unscheduled flows—discrepancies between contracted and actual power flows due to network impedance—which can cause congestion and limit transactions. They could maintain line flow within specified limits, mitigating loop flow effects.
Enforcement of Contractual Flows	These controllers could ensure that power flows along designated transmission paths adhere to contractual agreements.
Dynamic Stability Enhancement	With the ability to modify the effective line impedance on tie-lines, APFCs could improve dynamic stability by dampening power oscillations.
Renewable Energy Integration	APFCs could facilitate the swift integration of renewable energy sources by unlocking grid capacity through flow redistribution.
Adaptive Expansion Solutions	Modular and scalable APFCs can help attain more flexible and adaptable transmission solutions that can accommodate future system conditions or unforeseen situations with less capital investment while maintaining reliability.
Maintenance and Construction Mitigation	APFCs could be rapidly deployed as cost-effective interim solutions to maintain reliability during critical transmission project delays or mismatches in project initiation timelines.
Synergy with other GETs	Complementing technologies like Dynamic Line Ratings and Topology Optimization, APFCs could enhance grid utilization and expedite grid development.

IMPLEMENTATION AND INTEGRATION ASPECTS

Numerous system studies have highlighted the economic advantages of APFCs across various applications. Nonetheless, APFCs are a 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 and performance, and no industry-wide specifications and standards for APFC have been developed and implemented yet. Further, there are no well-established practices and guidelines to inspect, maintain, and assess assets over time, including life expectancy, replacement strategy, and end-of-life removal/disposal.

Operation and Control Strategies	Planning Criteria, Models, and Methodology	Cybersecurity Assessments
Asset Management and Labor Training	Cost/Benefit	Market Impacts and Incentives

From the operation perspective, there is a need to develop strategies and approaches to control and operate multiple APFCs when they are used in a meshed power network to manage wide-area power flows. This includes the self and cross-sensitivity factors of each APFC, where overlapping areas of influence necessitate careful control strategies. Centralized or decentralized control schemes may be implemented depending on the application objective. In any case, the communication between field devices and system operators must be securely cyber-protected, and the potential for communication loss must be assessed.

A methodical approach, including a thorough cost-benefit analysis, is essential to determine the optimal locations, sizes, and types of technology for specific use cases, facilitating seamless integration into the grid. Metrics and criteria for technical and economic comparison with other alternatives are essential for planning analysis. In addition, dynamic flow adjustments during operations can influence day-ahead and real-time markets, and market dynamics and must be properly considered. Participation models that can allow for incentives to operate APFC in a way that maximizes economic efficiency and reliability are to be developed and implemented.

AREAS FOR GROWTH

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. The following are potential areas for development and expansion, aiming to expedite the acceptance and growth of these technologies within the power grid:

1. **Reliability and Availability Test Methods:** What test methods are needed to confirm the performance, reliability and availability of devices under various environmental and operating conditions?
2. **Technology Selection:** What are the essential characteristics to consider when choosing a technology provider? Are there established selection criteria, performance metrics, or industry standards?
3. **Modeling and Representation:** How should APFCs be modeled in various tools for different types of analysis and studies?
4. **Comparative Assessment:** How should APFC be evaluated and compared with other potential alternatives?
5. **Operational Best Practices:** What are the established best practices and guidelines for operating and controlling these devices?
6. **Market Impact:** How would dynamic changes in power flows affect market dynamics? What type of incentives need to be implemented to promote investment and operation of APFCs, in a way that benefits outweigh costs any potential risks?

Recognizing these opportunities for advancement, EPRI's GET SET initiative is set to prioritize a series of research and development activities aimed at enriching the collective understanding and application of APFCs:

1. **Collaborative Field Deployments:** Foster ongoing collaboration with utilities and technology providers to ensure reliable and safe field deployments, documenting lessons learned.
2. **Operational Best Practices Development:** Formulate best practices for the operation of APFCs in day-ahead and real-time markets. Generate guidelines for the operation and control of multiple APFCs.
3. **Comprehensive Planning Framework:** Establish a planning framework for designing APFC-based transmission solutions, encompassing processes, models, tools, analysis, data, control design and implementation, and economic assessments across different technology providers.

4. **Model Development:** Advance the development of planning and Energy Management System (EMS) models.
5. **Create a APFC User Group:** A forum where existing and prospective users can share experiences helping increase understanding, improving the technology and the application.
6. **Performance and Reliability Characterization:** Develop relevant performance requirements and functional specifications for APFC devices, as well as installation, maintenance, and replacement strategies.
7. **Laboratory Testing:** The development and execution of test capabilities where designs can be quickly tested to confirm performance and reliability under a range of environmental and operating conditions. These tests are not only important for new designs, but they assist in evaluating design improvements and changes prior to deployment.

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

Developing Specifications

Technology Selection

Identifying Cybersecurity Requirements

Maintenance Practices

Disseminating Lessons Learned

Criteria to Measure Performance

Benefits and Risks

Impact on Protection Schemes

Planning and EMS Models

Optimal Size and Location

Full-Scale Tests with Utilities

Staff Training

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EPRI CONTACTS

ALBERTO DEL ROSSO, *Program Manager*
865.218.8137, adelrosso@epri.com

SWAROOP GUGGILAM, *Staff – Level V*
865.218.5905, sguggilam@epri.com

ANNA LAFOYIANNIS, *Technical Leader I*
980.495.7437, alafoyiannis@epri.com

For more information, contact:

EPRI Customer Assistance Center
800.313.3774 • askepri@epri.com

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EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • www.epri.com

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