U.S. DEPARTMENT OF
ENERGY
OFFICE OF
ELECTRICITY

Transformer Resilience and Advanced Components (TRAC) Program

Vision and Framework

June 2020



ACKNOWLEDGEMENTS

The Transformer Resilience and Advanced Components (TRAC) Program Vision and Framework for the U.S. Department of Energy (DOE) Office of Electricity (OE) was developed through information gathered and review comments received from a broad range of stakeholders. DOE would like to acknowledge the various organizations and their representatives for their contribution to this document.

ABB Inc.
Ames National Laboratory
AMSC
Argonne National Laboratory
Bonneville Power Administration
Booz Allen Hamilton
Carnegie Mellon University
Case Western Reserve University
Clemson University
ComEd
Concurrent Technologies Corp
ConEd
Copper Development Association
Critical Materials Institute
CURENT, UTK
Dow Chemical Company
Duke Energy
Duquesne Light
Eaton
Energetics Incorporated
EPB
EPRI
Florida State University
GE Global Research
General Cable
General Electric
Georgia Institute of Technology
Google X
Gridco Systems
HRL Laboratories LLC
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
Mitsubishi Electric Power Products Inc.
Nanofoundry, LLC
National Electrical Manufacturers Association
National Energy Technology Laboratory
National Institute of Standards and Technology
National Renewable Energy Laboratory
NC State University/FREEDM Center
New York Power Authority
Oak Ridge National Laboratory
Resilient Power Systems
S&C Electric Company
Salt River National Laboratory
Sandia National Laboratory
Savannah River National Laboratory
Schneider Electric
SD Meyers
Siemens
Silicon Power Corporation
Southern California Edison
Southern Company
Tibbar Plasma Technologies, Inc.
Texas A&M University
The University of Tennessee
U.S. Department of Energy
U.S. Department of Homeland Security
University of Arkansas
University of Central Florida
University of Denver
University of Houston
University of Pittsburgh
University of Tennessee
Vanderbilt University

(This page intentionally left blank)

EXECUTIVE SUMMARY

This Vision and Framework document describes the research and development (R&D) opportunities, goals, and key activities that fall within the scope of the Office of Electricity (OE) Transformer Resilience and Advanced Components (TRAC) program.[1] To date, much of the "smart grid" transformation has focused on applying advanced digital information and communication technologies to the power grid to improve the system's reliability, resiliency, efficiency, flexibility, and security. To realize the full potential of a modernized grid, advances in the grid's physical hardware are also needed. One prime example is the development and use of utility-scale energy storage systems. Next-generation grid components can improve equipment performance and lifetimes over current designs, simplify integration of advanced technologies, and provide new capabilities required for the future grid. The activities identified in this document can help accelerate grid modernization, increasing controllability, flexibility, and resilience, and realize the vision of the TRAC program.

The TRAC program supports activities in high-impact focus areas where Federal resources, subject to Congressional appropriations, can play an important role in filling critical R&D gaps. The application areas and technologies highlighted in this document were identified through meetings and discussions with various stakeholder groups representing industry, academia, and National Laboratories, and through the U.S. Department of Energy's Quadrennial Technology Review process.[2] Under each application area are specific technologies (see Table ES-1) that, if objectives are met, can address some of the major challenges facing the industry, establish capabilities needed in the future, and enable new operational paradigms.

VISION STATEMENT

Technologies and approaches will be developed that help maximize the value and lifetimes of existing grid components, and enable the next-generation of grid hardware to be more adaptive, more flexible, self-healing, resilient to all-hazards, reliable, and cost-effective compared to technologies available today.

---

[1] U.S. Department of Energy, Office of Electricity, "Transformer Resilience and Advanced Components (TRAC) Program," available at https://www.energy.gov/oe/services/technology-development/transformer-resilience-and-advanced-components-trac-program.

[2] U.S. Department of Energy, *Quadrennial Technology Review 2015*, available at http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015.

Across the various application areas, there are several desired attributes associated with the design of next-generation transmission and distribution (T&D) grid technologies that will influence and shape the R&D activities within the TRAC program portfolio, including the following:

- Modularity and scalability
- Local intelligence and adaptability
- Inherent cyber-physical security
- Manufacturability and sustainability

Standardized designs do not exist for many T&D grid components, and their customized nature drives up equipment and installation costs. Modular and scalable designs would enable greater standardization and allow for more cost-effective capacity expansion. Additionally, local intelligence with embedded sensors, data processing, and communications would enable real-time health monitoring, reducing maintenance costs and enhancing system reliability by preventing failures.

With increased intelligence, future T&D grid components will have much stronger connectivity to communication and information technology networks. To mitigate vulnerabilities from evolving threats, cyber and physical security measures must be considered simultaneously and incorporated into the design of each component, rather than added as an afterthought. Finally, as new T&D grid components are designed and developed, it is important to consider the manufacturing processes and lifecycle impact of these technologies.

Table ES-1. TRAC Program Focus Areas, Technologies, and Objectives

R&D Focus Areas	Application Areas	Technologies	Objectives
Power Electronics	**Advanced Transformers**	Flexible and Adaptable Large Power Transformers	• Costs comparable to conventional units (*e.g.*, \$10–\$15 per kilovolt-amps [kVA]) • Efficiency >99% at all levels of loading • 25% reduction in size, weight, and footprint compared to conventional units • Controllable impedance range of 5%–21%
		Power Electronics Augmented Distribution Transformers	• Costs comparable to conventional units (e.g., \$25–\$35 per kVA) • Efficiency greater than prescribed standards at all levels of loading • Double the power density compared to conventional units • Self-protected against switching failures
		Solid State Power Substations	• System capital costs of \$80–\$100 per kVA • Efficiency >97% at all levels of loading

R&D Focus Areas	Application Areas	Technologies	Objectives
			• Module galvanic isolation > 100 kilovolt (kV) at high frequencies • Half the footprint of a conventional substation
	Low-Cost Power Flow Controllers	Advanced Power Routers	• System capital costs of $10–$40 per kVA • Impedance control in the range of 10%–20% of power rating • Response times < 5 milliseconds
		Medium-Voltage Direct Current Converters	• Installed system costs < $100 per kVA • Efficiency > 99% at all levels of loading • Half the footprint of a converter station built with conventional converter technologies
Materials	**Advanced Components**	Dielectrics and Insulators	• Dielectric strength of > 120 kV per centimeter (kV/cm) at the same price as conventional materials • Dielectric loss angle (tan delta) of < 0.05% at 60 hertz (Hz) at upper limit of operating conditions • Enhanced material properties remain stable over useful life of assets (*e.g.*, 20–40 years) • Temperature withstand > 130°C in continuous operation, > 180°C in emergency situations
		Magnetics	• 50% reduction in energy losses for line frequency transformers compared to silicon steel at the same flux density • 50% reduction in eddy current losses for high power (kilowatts to megawatts), high frequency (10–100 kilohertz (kHz)) transformers compared to state-of-the art materials • Costs comparable to materials used today
		Electrical Conductors	• Electric conductivity 50% better compared to copper or aluminum • Mechanical strength and thermal conductivity 25% better compared to copper or aluminum • Costs comparable to copper or aluminum
		Semiconductor Devices	• Packaged diodes and transistors that cost < $0.10/amp at 1,200 volts (V) • Packaged diodes and transistors that can block > 5 kV and carry > 20 amps (A)

R&D Focus Areas	Application Areas	Technologies	Objectives
			• Packaged transistors with switching frequencies up to 100 kHz and low losses
Sensors	**Enhanced Monitoring**	Sensing Elements	• Accuracy better than 1% of critical value of interest • Capital cost < $1 per sensing element for ubiquitous sensors • Sensor capital cost and lifetime commensurate with instrumented equipment and application
		Integrated Data Processing and Communications	• Installed costs < $100 per sensor system • Installed costs < $10,000 per instrumented grid node (e.g., substation and facility) • Support up to 10,000 nodes without performance degradation • Communication latency < 1 millisecond within 10 miles
		Analytics and Applications	• Autonomous adjustment and control to prevent unwanted events in < 5 milliseconds • Better than 99% success rates in the detection of and the protection against targeted events • Improved analytics result in > 5% savings in asset management on average

In addition to the R&D needed for these application areas, there are a range of supporting activities and issues that will require consideration and attention to achieve broader adoption of innovations. These activities and issues are organized into five key categories: (1) testing and model validation; (2) simulations and analyses; (3) architectures, interoperability, and standards; (4) manufacturing and supply chain; and (5) education and training. Efforts in these supporting areas will be coordinated with R&D to amplify results that can lead to benefits, including:

- Increased energy efficiency
- Improved operations
- Enhanced asset utilization and management
- Increased system resilience
- More domestic manufacturing and jobs

Federally sponsored R&D, along with supporting activities, can complement industry efforts and help (1) promote innovation, (2) de-risk technologies that could provide significant value to the Nation, and (3) facilitate broader adoption of new technologies and approaches.

The investment cycle needed to replace, upgrade, and expand the U.S. T&D systems has already begun, with annual spending increasing from $28 billion in 2010 to approximately $44 billion in 2013. Missing this window of opportunity to develop and install the next-generation of T&D components required for a future grid could slow its transformation and pose significant opportunity costs to society.

Through basic and applied R&D that effectively address industry's need for enhanced T&D hardware performance and capabilities, the TRAC program will support advancement of more reliable, resilient, and flexible grid component technologies by leveraging innovative designs with power electronics, new materials, and embedded sensors and intelligence.

(This page intentionally left blank)

CONTENTS

Figures

Tables

1. PROGRAM OVERVIEW

The U.S. electric power system consists of an extensive infrastructure of more than 22,000 generators; 55,000 substations; 642,000 miles of high-voltage lines; and 6.3 million miles of distribution lines that serve 153 million customers (see Figure 1).[3, 4] To date, much of the "smart grid" transformation has focused on applying advanced digital information and communication technologies (ICT) to the power grid to improve the system's reliability, resiliency, efficiency, flexibility, and security. To realize the full potential of a modernized grid, advances in the grid's physical hardware are also needed. One prime example is the development and use of utility-scale energy storage systems. Next-generation grid components can improve the performance and lifetimes over current designs, simplify integration of advanced technologies, and provide new capabilities required for the future grid.

Transformers, power lines, and other substation equipment (i.e., grid hardware components) are often exposed to the elements and are vulnerable to an increasing number of natural and man-made threats. To ensure a reliable and resilient electric power system, next-generation grid components need to be designed and built to better withstand and rapidly recover from the impact of lightning strikes, extreme terrestrial or space weather events, electrical disturbances, accidents, equipment failures, deliberate attacks, and other unknowns. Failure of key components can lead to widespread outages and long recovery times.

The Office of Electricity's (OE's) Transformer Resilience and Advanced Components (TRAC) program accelerates modernization of the grid by addressing challenges associated with large power transformers (LPTs), critical components, and other grid hardware technologies. As the grid evolves to enable a more resilient, secure, and clean energy future, R&D is needed to understand the physical impact these changes have on LPTs and other equipment, and to facilitate the adoption of new technologies and approaches. Development of advanced grid components will provide the enhanced capabilities required for the future grid, increasing controllability, flexibility, and resilience, and help avoid infrastructure "lock-in" with outdated technologies that are long-lived and expensive.

The TRAC program has two primary goals:

- Increase the resilience of aging assets and identify new requirements for future grid components
- Accelerate the research, development, and field validation of next-generation grid hardware technologies

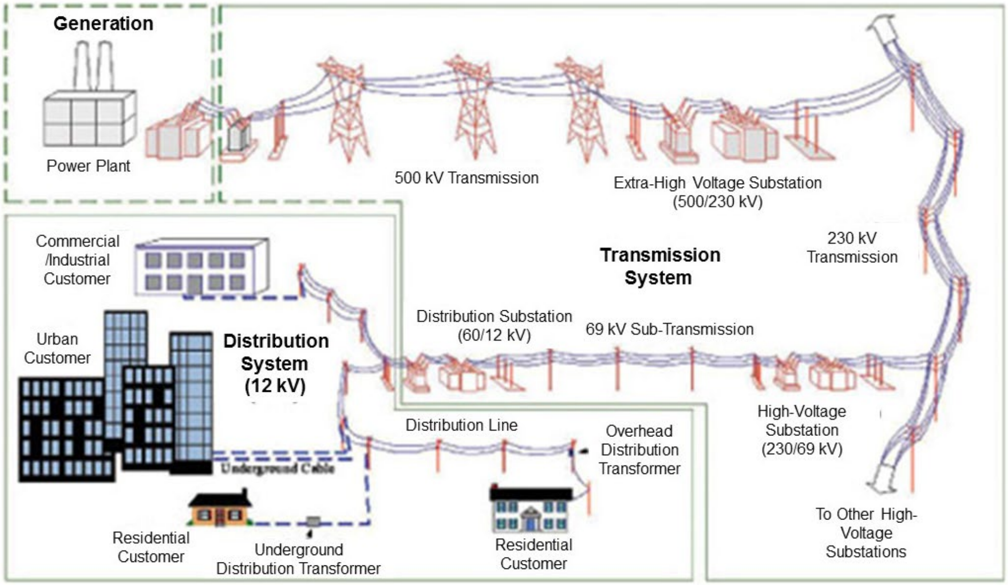
---

[3] U.S. Energy Information Administration, *Electric Power Annual 2018* (Oct. 2019) (rev. Mar. 6, 2020), https://www.eia.gov/electricity/annual/pdf/epa.pdf.

[4] U.S. Department of Energy, "Quadrennial Energy Review – Appendix C – Electricity," (Apr. 2015) https://www.energy.gov/sites/prod/files/2015/09/f26/QER_AppendixC_Electricity.pdf.

VISION STATEMENT

Technologies and approaches will be developed that help maximize the value and lifetimes of existing grid components, and enable the next-generation of grid hardware to be more adaptive, more flexible, self-healing, resilient to all-hazards, reliable, and cost-effective compared to technologies available today.



Source: Federal Energy Regulatory Commission

Figure 1. Segments of the Electric Power System

This document presents the rationale, opportunities, objectives, and key activities of the TRAC program. It frames the application needs and technology challenges that can have a significant impact on the industry if addressed. It also includes the organizing framework of activities needed to effectively and holistically overcome grid hardware challenges to realize TRAC program goals.

While serving as a snap-shot in time of critical R&D gaps, the technology objectives identified are performance milestones that can guide program activities and if met, spur industry adoption of innovations. This document is not meant to serve as a technical roadmap which provides a detailed path to advance a certain technology. It is also not a multi-year program plan that lays out activities over a fixed time period with a specific amount of resources.

1.1 Program Context

Future economic growth, public health and safety, and the energy security of the United States demands evolution and revolution in both grid hardware and software technologies to ensure reliable, affordable, secure, and diverse electric power delivery. Recent advances in ICT have been applied to the grid, increasing situational awareness and enabling more optimal operations. While these "smart grid" technologies are being deployed, evolving capabilities, changing system demands, and the adoption of other new technologies require greater flexibility, agility, and adaptability from the U.S. electric grid. Current major trends facing the electric power system include the following:

- *Changing demand* driven by population growth, adoption of energy-efficient technologies, dynamic economic conditions, broader electrification, and the potential mass market availability of electric vehicles
- *Changing generation mix*, including resource type (e.g., renewable, nuclear, oil and natural gas, and coal) and location (e.g., centralized, distributed, and off-shore), of the Nation's generation portfolio driven by technology, market, and policy developments
- *Increasing variability of generation and load patterns*, including the integration of variable renewable energy sources, more active consumer participation, and the accommodation of new technologies and techniques
- *Increasing risks to electric infrastructure*, such as more frequent and intense extreme weather events, cyber threats, physical attacks, and growing interdependencies with natural gas and water infrastructure
- *Aging electricity infrastructure* that is rapidly becoming outdated in light of the other changes happening system-wide, introducing greater vulnerabilities

These trends present challenges as well as opportunities to advance the capabilities of today's electric grid, especially transmission and distribution (T&D) components. The changing landscape of generation and load-side technologies is fundamentally altering the electric power flows and physical phenomena for which existing grid components were designed to accommodate. The increased connectivity between cyber and physical systems necessitates a more holistic approach to designing for security and resilience, and the pace of grid modernization and system changes demand hardware solutions that are more flexible and adaptable. During this period of transition, R&D of next-generation grid components will play a critical role in shaping the future grid and enabling new operational paradigms.

These various power system trends present unique challenges to the electric industry that prompt the need for the TRAC program. Some of these challenges and their potential impacts on grid T&D components are summarized in Table 1. Transmission is defined as the grid spanning from generator substations through to the high-voltage side of distribution substations. Distribution is defined as the grid from distribution substations through to a customer meter.

Table 1. Impacts on Transmission and Distribution Components

Challenges	Transmission Component Impacts	Distribution Component Impacts
More Variable Renewable and Distributed Energy Resources	• Line congestion during large swings in power generation • More susceptible to instability due to lower system inertia and reduced frequency response • Greater transfer capacity needed • Increased harmonics	• Increased operation of load tap changers and capacitor banks • Bi-directional power flows • Phase imbalances on feeders • Greater range of operational requirements such as fault handling capabilities • Increased harmonics
Fast Rate of System Changes with Slow Grid Infrastructure Upgrades	• Custom designs due to concerns with backwards compatibility • Conservative upgrades due to uncertainty in need and location	• Interoperability concerns with the diversity of new technologies • Upgrades based on least-cost due to uncertainty in need and location
More Frequent and Extreme/Abnormal Weather Events and Physical Attacks	• Higher frequency of damage and disruptions from wind and ice • Higher operating temperatures during heat waves and rapid aging • Unpredictable points of failure	• Higher frequency of damage and disruptions from trees and floods • Increased number of faults • Higher operating temperatures during heat waves and rapid aging
Greater Reliance on Information and Communication Technologies	• Susceptible to cyber attacks and electromagnetic pulses (EMP) • Synchronized timing (Global Positioning System) and component awareness needed	• Susceptible to cyber attacks and EMP • Data overload and system management issues with the large amount of "smart" devices
Greater Environmental Constraints and Desire for Sustainability	• Restrictions on insulation and cooling materials • Limited right-of-way for new infrastructure investments	• Restrictions on insulation and cooling materials • Greater demand for efficient and flexible technologies

1.2 Program Scope

The TRAC program is focused on enhancing and advancing the components and technologies that make up the electric power T&D infrastructure (i.e., grid hardware). These assets are physically responsible for carrying and controlling the electrons that deliver electric power within the electric power system. Specific technologies include, but are not limited to, transformers, cables and conductors, power flow and voltage controllers, protection equipment and switchgear, and equipment sensors. To realize the full potential of transforming to the grid of the future, these hardware components will need to evolve by leveraging innovative designs, new materials, and embedded intelligence.

While advances in communication and control systems, cybersecurity, and energy storage are all critical to grid modernization, these technologies and tools are not directly addressed within the TRAC program; they are covered under other U.S. Department of Energy (DOE) R&D programs.[5] However, the evolution of these technologies, their impact on existing equipment, and their integration with T&D components is considered and will influence TRAC program activities. For example, research of advanced transformers and their integration with energy storage systems are within the scope of the TRAC program, but the research of the energy storage system itself is not. Furthermore, cybersecurity requirements will be incorporated into the R&D of next-generation T&D components, but the advancement of cybersecurity solutions will not be pursued under the TRAC program.

To better define the program scope, several categories of grid hardware technologies and their basic functionality are described in more detail below.

1.2.1 Transformers

Transformers are one of the fundamental building blocks of the electric grid; essentially all electric energy delivered flows through at least one. Through electromagnetic coupling, these components change the voltage of electric power, increasing it to transmit electricity more efficiently over long distances and decreasing it to a safe level for final delivery to end users. There are generally two categories of transformers—power transformers and distribution transformers—but there are a range of voltage classes within these categories (see Table 2). Power transformers are optimized for high efficiencies and are typically located at generator plants and within substations, making them critical infrastructure assets from a resiliency standpoint. Distribution transformers are designed to accommodate a wide range of loading conditions and are typically located on poles and in enclosures within industrial, residential, and commercial areas, directly supplying power to the end user at low or medium voltages.

Table 2. Overview of General Grid Transformer Groups[6,7]

Type	Class	Voltage Ratings
Power Transformers	Extra High Voltage	345–765 kV
	High Voltage	115–230 kV
	Medium Voltage	34.5–115 kV
Distribution Transformers	Distribution Voltage	2.3–34.5 kV

---

[5] U.S. Department of Energy, Office of Electricity, https://www.energy.gov/oe/office-electricity.

[6] U.S. Department of Energy, Infrastructure Security and Energy Restoration, Office of Electricity Delivery and Energy Reliability, "Large Power Transformers and the U.S. Grid" (Apr. 2014), http://energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf.

[7] Distribution transformers are covered by the standard defined at 10 CFR 431.192.

1.2.2 Cables and Conductors

Extra-high and high-voltage cables and conductors are the primary carriers of electric power and are critical for the reliable, efficient, and cost-effective delivery of electricity. Overhead line conductors are suspended from towers and poles and are generally not insulated except at lower voltage levels (i.e., within distribution systems). In contrast, shielded cables are always insulated and are generally used in underground applications, such as in dense urban areas where real-estate costs, safety concerns, and aesthetics restrict the use of overhead lines. Underground cables are also used in applications where overhead lines are hard to locate, such as water crossings, and are increasingly considered advantageous for their resilience to wind and ice storms.[8]

1.2.3 Power Flow and Voltage Controllers

In a passive electric grid, power flows according to the laws of physics and follows the path of least resistance. This means that the amount of power that can flow between two points on the grid is limited by the weakest line, despite the existence of other paths. For the transmission system, active control can be achieved by changing the physical connections of the network (a mechanical-based process) or by using power electronics-based systems such as high-voltage direct current (HVDC) converters and flexible alternating current transmission system (FACTS) devices. HVDC converters decouple power flows from the synchronous nature of the grid, enabling directed transfers, whereas FACTS devices work within the synchronous nature of the grid and alter line impedances to control power flows.

In distribution systems, which are typically radial and not networked (except in dense urban centers), power normally flows in one direction and voltage controllers are used to ensure line voltages stay within limits along distribution feeders. Similar to the transmission system, active control on distribution systems can be achieved through mechanical-based or power electronics-based technologies known as custom power devices. Transformers with tap-changers, switched capacitors and inductors, and voltage regulators are mechanical-based technologies that provide a coarse level of control, while their more expensive power electronics-based equivalents can provide much finer levels of control.

1.2.4 Protection Equipment and Switchgear

Technologies such as circuit breakers, surge arresters, and fault current limiters help to protect substation components and electric power equipment from damage. Fuses, sectionalizers, and reclosers provide similar protective functions within distribution systems and help to isolate faults, preventing disturbances from propagating into larger outages. Undesirable or excessive current flows or over-voltages arising from natural events (e.g., lightning strikes or geomagnetic disturbance), system operations (e.g., switching surges or transients), or fault conditions (e.g., an unintentional short circuit or partial short circuit) can cause permanent or catastrophic damage to grid components.

---

[8] Polansky, D., and B. Richardson, "Stormy Weather: Intelligent Undergrounding Supports System Reliability and Resiliency," Electric Energy T&D Magazine, 18, no. 5 (Sept.–Oct. 2014), http://www.electricenergyonline.com/show_article.php?mag=101&article=820.

Circuit breakers are automatically operated electrical switches designed to open when there is an overload or short circuit. Surge arresters discharge over-voltages that can occur on the system by providing a path to ground when an undesirable voltage level is reached. Fault current limiters restrict the amount of current that can flow within an electrical pathway during faults. Fuses are one-time use devices that open under a short circuit and must be replaced, while reclosers are smarter and attempt to clear temporary faults. Sectionalizers work with reclosers or circuit breakers to isolate parts of the grid under permanent fault conditions to limit the extent of an outage.

1.2.5 Equipment Sensors and Protection

Grid-related sensors (e.g., phasor measurement units, potential transformers, and current transformers) help measure a range of electrical system parameters such as voltage, current, real and reactive power, frequency, and phase angles. These parameters can be used to identify harmonic distortions, power factors, power flows, fault conditions, and over-voltages, which are critical to ensuring optimal operating conditions and system protection. Local sensors and relays detect these abnormal conditions and are used to trigger the action of certain protection equipment, such as circuit breakers. Sensors can also be deployed within equipment to monitor the health and condition of assets by measuring temperature, pressure, mechanical stress, moisture, chemical signatures, and other non-electrical parameters.

1.3 Program Benefits

The Brattle Group, in a report for the Edison Foundation, estimated that the electric utility industry will need to spend about $1.5 to $2 trillion from 2010 to 2030 just to maintain the reliability of electric service.[9] This does not include the additional billions that customers may spend on end-use equipment and generation and automation behind the meter. The investment cycle needed to replace, upgrade, and expand the U.S. T&D systems has already begun, with annual spending increasing from $28 billion in 2010 to approximately $44 billion in 2013.[10] Missing this window of opportunity to develop and install the next-generation of T&D components required for a future grid could slow its transformation and impose significant opportunity costs to society.

Advances and innovation in the various T&D components within the TRAC program scope can provide numerous benefits to the electric power system, its customers, and society. If next-generation technologies with enhanced performance and capabilities become cost-effective, the potential benefits associated with their use include the following:

---

[9] The Brattle Group for The Edison Foundation, "Transforming America's Power Industry: The Investment Challenge 2010-2030 – Executive Summary" (Nov. 2008), https://brattlefiles.blob.core.windows.net/system/publications/pdfs/000/004/864/original/transforming_americas_power_industry_exec_summ_nov_2008.pdf?1378772136.

[10] Harris Williams & Co., "Transmission & Distribution Infrastructure" (2014), http://www.harriswilliams.com/sites/default/files/industry_reports/ep_td_white_paper_06_10_14_final.pdf.

- **Increased energy efficiency** – In the United States, approximately 5% of generated electricity is lost in the delivery of power.[11] Improvements in transformer efficiency, lower resistance in high-voltage cable and conductors, and elimination of loop flows can decrease these losses. Reducing these losses by 20% can save at least $4.2 billion.[12]
- **Improved operations** – During periods of high demand, bottlenecks can develop on the transmission system that prevent access to lower-cost energy resources, such as wind and solar. These congestion costs can be quite significant, with PJM reporting average annual congestion costs of more than $1.1 billion over the last decade.[13] Greater deployment of power flow controllers can reduce system congestion and optimize generator dispatch.
- **Enhanced asset utilization and management** – Power flow through grid equipment is usually constrained to a lower limit due to reactive power considerations and reliability requirements under varying system conditions. Greater deployment of power flow controllers, enhanced asset condition monitoring, and intelligent equipment can defer system upgrades and reduce maintenance costs.
- **Increased system resilience** – Power outages and damage from weather-related events and other causes have been estimated to cost the United States $28–$169 billion annually.[14] Increased knowledge of component vulnerabilities, better equipment designs that facilitate recovery, and smarter protection equipment can reduce outage and restoration costs. Additionally, greater deployment of power flow controllers can route power around affected areas and continue to provide electricity to critical loads and increase system stability in the event of a contingency.
- **More domestic manufacturing and jobs** – Research and development that lead to commercialization of next-generation T&D components can reinvigorate the U.S. manufacturing sector and create new jobs as the existing infrastructure is replaced. Advanced grid hardware components that utilize new designs, have embedded intelligence, and leverage material innovations such as wide band gap semiconductors, high temperature superconductors, and high frequency magnetics can increase demand for skilled labor.

---

[11] U.S. Energy Information Administration, "Independent Statistic & Analysis—U.S. Energy Information Administration", https://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3.

[12] Based on 5% transmission losses; Rolling 12 month generation at utility scale facilities, ending January 2020, of 4,118,051 thousand megawatt hours – U.S. Energy Information Administration, "Electric Power Monthly," https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1; 10.29 cents per kilowatt-hour national average rate in January 2020 – U.S. Energy Information Administration, "Electric Power Monthly," https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

[13] Monitoring Analytics, *2017 State of the Market Report for PJM*, tbl. 11-9, at 510 (2017), http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2017/2017-som-pjm-sec11.pdf.

[14] Executive Office of the President, *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages,* p. 17 (Aug. 2013), http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf.

1.4 Role of Federal Investments

The current business-as-usual trajectory for the electricity industry will not result in an efficient or timely transition to a modernized grid and the realization of the benefits described above. Grid technology innovation is inhibited by a fragmented industry and private investment uncertainties. A survey conducted by the National Science Foundation showed that the utility industry invests just 0.1% of its net sales in R&D.[15] While there are several major players in the T&D component space, incumbents tend to invest in incremental R&D and not on transformative solutions. Additionally, the small number of innovators that may pursue novel grid component technologies may find it difficult to acquire sufficient resources to scale absent Federal involvement.

Since the Clean Tech boom of 2006–2011, a majority of venture capital firms have lost their appetite for clean energy innovation, especially those associated with new materials and processes.[16] Ultimately, private sector capital in isolation is not the best mechanism to develop breakthrough grid component innovations. This is primarily the result of two conditions: a utility business model that focuses on limiting short- and medium-term costs, and the high risks of hardware innovations needing large up-front capital investments in a rate-payer-oriented market.

Federally sponsored R&D, in partnership with private entities, can complement industry efforts and help (1) promote innovation, (2) de-risk technologies that could provide significant value to the Nation, and (3) facilitate broader adoption of new technologies and approaches.

Through basic and applied research and development that effectively address industry's need for enhanced T&D hardware performance and capabilities, the TRAC program will support advancement of more reliable, resilient, and flexible grid components by leveraging innovative designs with power electronics, new materials, and embedded sensors and intelligence.

---

[15] National Science Foundation, "Business Research and Development and Innovation: 2014, Detailed Statistical Tables," NSF 18-302 (Mar. 12, 2018), https://www.nsf.gov/statistics/2018/nsf18302/pdf/nsf18302.pdf.

[16] Gaddy, Benjamin, Varun Sivaram, and Francis O'Sullivan, *Venture Capital, and Cleantech: The Wrong Model for Energy Innovation*, MIT, An MIT Energy Initiative Working Paper (July 2016), http://energy.mit.edu/wp-content/uploads/2016/07/MITEI-WP-2016-06.pdf.

2. APPLICATION AREAS AND TECHNOLOGY OBJECTIVES

The TRAC program supports activities in high-impact focus areas (i.e., power electronics, materials, and sensors) where Federal resources, subject to Congressional appropriations, can play an important role in filling critical R&D gaps. The application areas highlighted in this document (see Figure 2) were identified through meetings and discussions with various stakeholder groups representing industry, academia, and National Laboratories, and through the DOE's Quadrennial Technology Review process.[17] Under each application area are specific technologies that, if objectives are met, can address some of the major challenges facing the industry, establish capabilities needed in the future, and enable new operational paradigms. These technologies are not meant to be exhaustive of industry needs (see Appendix for other opportunities) and will change as research progresses and as the grid evolves.

The research needs in the highlighted application areas are described in this section along with objectives that indicate significant milestones in the development of associated technologies. In addition, there are several desired attributes associated with the design of next-generation transmission and distribution (T&D) grid components that will influence and shape the R&D activities within the TRAC program portfolio, including the following:

- Modularity and scalability
- Local intelligence and adaptability
- Inherent cyber-physical security
- Manufacturability and sustainability

Standardized designs do not exist for many T&D grid components, and their customized nature drives up equipment and installation costs. T&D grid components are also not designed with future capacity expansion in mind; upgrades typically entail replacing equipment in its entirety (i.e., removing an existing component and installing a new one with a higher power rating). Modular and scalable designs would enable greater standardization and allow for more cost-effective capacity expansion. Additional benefits include smaller module sizes for ease of transport and smaller power ratings to eliminate criticality.

Like most equipment, T&D grid components are designed to last for a specified lifetime assuming an average use profile. However, the exact timing of failures is nearly impossible to predict and routine maintenance is performed at regular intervals to assess component health. Local intelligence with embedded sensors, data processing, and communications would enable real-time health monitoring, reducing maintenance costs and enhancing system reliability by preventing failures.

---

[17] U.S. Department of Energy, *Quadrennial Technology Review 2015*, http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015.

Additionally, local intelligence can enable more adaptive capabilities such as dynamic protection schemes and "hot-swap" and "plug-and-play" design features.

With the value that "smarter" equipment can offer to utilities, including enhanced grid reliability, it is anticipated that future T&D grid components will have much stronger connectivity to communication and information technology (IT) networks. To mitigate vulnerabilities from evolving threats, cyber and physical security measures must be considered simultaneously and incorporated into the design of each component, rather than added as an afterthought. Modularity in designs can also decouple the cyber features from the physical asset to accommodate cyber/IT upgrades, which can occur much faster than hardware upgrades.

Finally, as new T&D grid components are designed and developed, it is important to consider the manufacturing processes, lifecycle, and environmental impact of these technologies. Many of the traditional materials used in grid components are metals, which can be recycled, but other materials such as inorganic transformer oil and sulfur hexafluoride (SF_6) used for electrical insulation pose a threat to the environment. Environmentally friendly materials (e.g., ester fluids and green gas for grid [g^3]) and sustainable designs will need to be utilized as grid components evolve. Additionally, as power electronic devices become more prevalent in grid equipment, their environmental impact at end-of-life should also be considered.

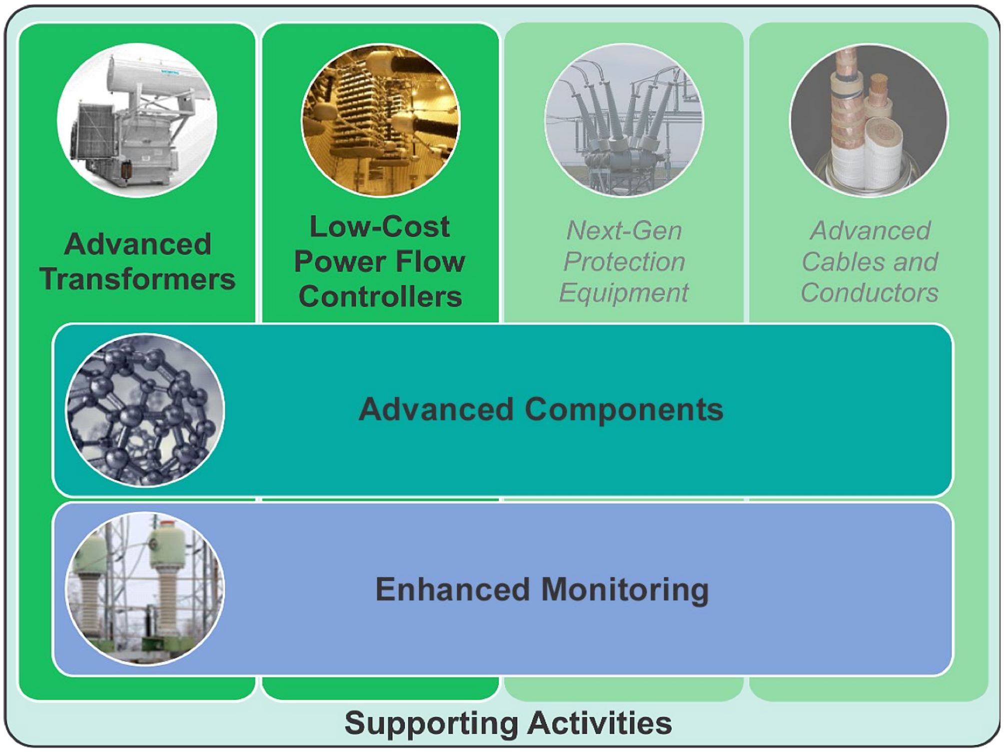


Figure 2. Application Areas in the TRAC Program (priorities in bold)

2.1 Advanced Transformers

Transformers are essential components in both the T&D systems. The electric grid has evolved and developed around the alternating current (AC) transformer, but increasing direct current (DC) generation sources and loads, including energy storage that can serve as both, will warrant new considerations for the functionality of these grid components and their coordination. As the grid evolves to accommodate more renewable and distributed energy resources and changing consumer loads, these ubiquitous components must also evolve. Transformers are ripe for innovation; they have been made with essentially the same materials and designs since the beginning of the electric power industry in the 19th century.

Greater penetration of variable renewables resources and clean energy technologies will affect the operating conditions in which transformers will need to be designed. For example, harmonic distortions produced by wind turbine generators, solar inverters, battery power conversion systems, and other factors often result in significant stray and eddy current losses that may contribute to premature failure of transformers.

Furthermore, mass market adoption of electric vehicles and customer-sited distributed generation may result in rapid changes in current and voltage, produce excessive loading, lead to phase imbalances, and cause overheating in distribution transformers.

There are three technologies identified for advanced transformers: (1) flexible and adaptable large power transformers, (2) power electronics augmented distribution transformers, and (3) solid state power substations.

BENEFITS AND OPPORTUNITIES:

- Develops smaller and lighter designs that are more efficient and easier to transport and install
- Improves power quality, system stability, and phase balancing to increase distributed renewable hosting capacity
- Removes or limits the criticality of substations for increased security
- Enables hybrid AC and DC circuits for enhancing efficiency
- Facilitates the formation of remote microgrids and enhances local resilience

CHALLENGES:

- Using advanced transformers in grid operations will require detailed testing and integration into energy management systems.
- Integrating multiple functions into a transformer will raise costs, and a viable business case is needed.
- Matching the reliability, cost, efficiency, and familiarity with traditional transformers will require substantive effort.

2.1.1 Technology 1—Flexible and Adaptable Large Power Transformers

Large power transformer (LPT) is a term used to describe a transformer with a power rating of 100 megavolt amperes (MVA) or greater, enough to supply more than 100,000 customers on average.[18] These critical components, in some conditions, may be vulnerable to electromagnetic pulses (EMPs), geomagnetic disturbances (GMDs), and switching transients from modern circuit breakers, as well as damage from extreme weather events (e.g., hurricanes and flooding). While damage to certain LPT components (e.g., bushings and oil

---

[18] One person has an average electrical power demand of 1kVa. Peak periods would be higher. Hollings, Gregory, “The Difference between Distribution and Power Transformers” (Sept. 27, 2013), http://www.abb-conversations.com/2013/09/the-difference-between-distribution-and-power-transformers).

conservators) can be repaired within a reasonable time, catastrophic failure of LPTs (e.g., damage to windings or insulation) could lead to widespread and long-term interruption of electric service.

LPTs are typically custom-made and are difficult to replace; procurement lead times are one year or more. Furthermore, their large size and weight make them difficult to transport, often requiring special permitting and equipment, which can add to costs and delays.[19] In the event of an emergency with multiple LPT failures, manufacturers may struggle to meet the demand for replacements in a timely manner. Because LPTs are generally tailored to customer specifications, they are not readily interchangeable with each other, and their high costs prohibit extensive spare inventories.

While utilities are implementing various methods and processes to mitigate risks associated with LPT failures (e.g., using four one-phase units to replace a single three-phase unit and participating in equipment sharing programs), development of more flexible and adaptable LPTs can facilitate transformer sharing and long-term replacement in the event of catastrophic failures, thereby increasing grid resilience. Expanding on industry efforts with resiliency transformers, there is an opportunity to fundamentally rethink and redesign LPTs to address other challenges that still exist.

R&D Needs:

Novel designs (e.g., integrated protection), materials (e.g., insulation), and components (e.g., bushings) to better withstand high-voltage and high-frequency transients (e.g., circuit break switching) and other off-normal conditions such as faults, GMD, and EMP

Novel designs (e.g., modularity), materials, and components that are more compact and lighter to address transportation concerns and site installation issues, and can also enable economies of scale to compress manufacturing timelines and reduce costs

System design standards that promote more standardized components, enabling greater flexibility in how equipment can be configured, interoperability between different vendor components, and more rapid repairs (e.g., bushing pocket designs for fast change-outs after failures)

Designs and components (e.g., integrated power electronics) that enable more flexible and adaptive capabilities such as connection to a range of high-side and low-side voltages, seamless integration with energy storage systems, and variable impedance to accommodate a broader range of operating locations and applications

---

[19] LPTs typically weigh between 100 and 400 tons. U.S. Department of Energy, *Large Power Transformers and the U.S. Electric Grid* (June 2012), http://energy.gov/sites/prod/files/Large%20Power%20Transformer%20Study%20-%20June%202012_0.pdf.

Objectives:

- Costs comparable to conventional units (e.g., \$10–\$15 per kilovolt-amp [kVA])
- Efficiency >99% at all levels of loading
- 25% reduction in size, weight, and footprint compared to conventional units
- Controllable impedance range of 5%–21%

2.1.2 Technology 2—Power Electronics Augmented Distribution Transformers

Distribution transformers provide the final voltage step-down of electric power prior to delivery to end users. These components are ubiquitous in distribution systems and have limited functionality and flexibility. As they are affected by stricter efficiency standards, experience more dynamic operating conditions from the integration of distributed energy resources (DERs), and are replaced after extreme weather events, there is an opportunity for innovation and upgrades with new capabilities.

Greater deployment of DERs presents challenges with voltage control and phase imbalances along distribution feeders. Conventional solutions use capacitor banks or load tap changers at the distribution substation to manage voltage changes, but solutions based on power electronics may offer greater flexibility and more dynamic control over many system parameters. When DERs are deployed at a customer site, the inherent DC nature of these resources (e.g., photovoltaic or energy storage) presents a good opportunity to use power electronics on the low-voltage side of distribution transformers to replace multiple inverters. However, these power electronics-based technologies have not been able to achieve the energy efficiency, robustness, or economic requirements needed for broader use.

Development of power electronics augmented distribution transformers, with power electronics at the low-voltage or high-voltage side or on both sides, could provide better power quality, enhance voltage regulation, and supply reactive power to facilitate DER integration. Additional capabilities could include the ability to transform radial topologies easily to more networked topologies, facilitating the transition to a more distribution-centric grid and enhancing resiliency. Networked topologies can also provide phase balancing and, potentially, protection features to handle changing fault conditions.

R&D Needs:

- Novel designs and construction materials to better withstand and recover from extreme weather events, enable systems that are more compact and lightweight for easier installation and deployment, and improve thermal management to enhance lifetime and performance

Adaptable system designs with easy connection interfaces and simple reconfiguration to allow operation in both radial and networked (meshed) mode, installation in both shunt and series configuration, and the ability to retrofit existing distribution transformers in the field

Novel power electronic circuit designs optimized for high efficiency at all levels of daily and extreme loading, along with advances in magnetic materials (e.g., high permeability and high resistivity) and windings to reduce hysteretic and eddy current losses

System designs with embedded sensors and intelligence that provide enhanced capabilities, including dynamic phase-balancing, voltage control, power factor correction, health monitoring, distribution system diagnostics, and will fail-normal

Novel designs (e.g., integrated protection and innovative shielding) and materials (e.g., magnetic core lamination) to provide enhanced voltage fault-ride through capabilities and improved robustness to lightning strikes, transients, and other off-normal conditions

Advanced coordination and control schemes, including system models, that leverage the enhanced capabilities provided by this technology and facilitate integration with distribution management systems

Objectives:

Costs comparable to conventional units (e.g., \$25–\$35 per kVA)

Efficiency greater than prescribed standards at all levels of loading[20]

Double the power density compared to conventional units

Self-protected against switching failures

2.1.3 Technology 3 – Solid State Power Substations

A transformer designed and built around the use of solid state devices (i.e., power electronics) affords the opportunity to integrate the functions of other pieces of equipment typically found within a substation in addition to a traditional AC power transformer. As such, this technology concept can be considered a solid state power substation (SSPS). This technology has the potential to revolutionize electricity delivery, replacing or enhancing the major nodes of the grid. SSPS technology could provide all the functions of traditional substations in a much

---

[20] U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. "Appliance and Equipment Standards Rulemakings and Notices," available at https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=55&action=viewcurrent.

smaller, integrated package at higher power densities, while also providing power flow control, power quality, protection, and fault handling capabilities.

SSPS technology is inherently modular and scalable in construction and can be deployed at the building level, the distribution level, and the transmission level. Their flexibility and adaptability can be used to incrementally expand the capabilities of existing substations, or be used to form hybrid AC and DC grids that offer the option of connecting to either current configuration (i.e., AC or DC) to enhance overall system efficiency. The integrated functionality of an SSPS can also enable the formation of microgrids, facilitating their integration at the point of common coupling and regulating the process of disconnecting and reconnecting, or be used to establish stand-alone microgrids for remote communities, defense applications, and aid the electrification of developing countries.

R&D Needs:

Novel designs and materials for high-power, high-reliability, high-functionality, compact, and low-cost power electronic modules, including the possibility of integration with energy storage elements, driver circuits, and embedded intelligence

Materials (e.g., magnetics) and designs for high-frequency, high-power (e.g., multi-megawatt applications) transformer cores used for galvanic isolation, and novel topologies and protection schemes for system designs without transformer cores

Modular architectures and designs with built-in redundancy to ensure high system reliability, integrated power filters, and other forms of protection to withstand lightning strikes, fault currents, transients, and surges from other system operations

Thermal management systems (e.g., air, water, and inductive cooling) and packaging to address high energy densities designs and modules, including solutions required for extracting heat from high frequency magnetic cores

Development of control coordination and use cases to avoid conflicts and assess value, and field validation of technical capabilities, including hybrid configurations (e.g., AC and DC circuits); the ability to augment/upgrade existing substation; and improved reliability and resiliency

Objectives:

System capital costs of \$80–\$100 per kVA

Efficiency >97% at all levels of loading

Module galvanic isolation >100 kV at high frequencies

Half the footprint of a conventional substation

2.2 Low-Cost Power Flow Controllers

Power flow controllers are proven technologies that can help direct electricity to where it is needed in a networked system. These components can help overcome challenges associated with more dynamic operating conditions caused by variable generation, power line congestion, loop flows, and reduced system inertia. They can also be used to defer capacity upgrades needed to meet increased peak demand. FACTS devices, including static volt ampere reactive (VAR) compensators (SVCs), static synchronous compensators (STATCOMs), and series compensation devices, along with HVDC systems are flow control technologies with a history of commercial success. However, these technologies are generally large with expensive installation, which limits the situations where they can be used.

Methods to reduce the costs associated with AC and DC power flow controllers, while enhancing their performance and reliability, can support broader deployment of these technologies. The future grid will need to accommodate both AC and DC sources and loads, requiring advancements in both AC and DC grid components that can help route power, optimize operations, and increase system reliability and resiliency. New applications, improved functionality, and added value streams can also support greater utilization of these technologies.

There are two technologies identified for low-cost power flow controllers: (1) advanced power routers and (2) medium-voltage direct current (MVDC) converters.

BENEFITS AND OPPORTUNITIES:

- Optimizes and increases the use of existing transmission assets to defer capital investments
- Enables more dynamic control of power flows to support greater renewable penetration
- Decouples and buffers the T&D systems so disturbances and faults do not propagate
- Enables more efficient power delivery into dense urban centers, especially with more native DC loads, such as electric vehicles

CHALLENGES:

- New coordination and control algorithms will be needed to support more complex system operations and markets enabled by power flow controllers.
- Ensuring the reliability of power flow controllers in response to transients and other electrical disturbances will require an active effort in protection.
- Optimizing the placement of power flow controllers will require detailed analysis and an understanding of their value.

2.2.1 Technology 1 – Advanced Power Routers

Retirement of large synchronous generators, such as coal-fired and nuclear power plants, and higher penetration of wind and solar generators are creating more dynamic conditions on the transmission system. The loss of system inertia results in frequency excursions that can happen quickly, requiring a high-speed response to prevent system instability after a contingency. Additionally, large voltage swings on transmission lines from large renewable energy systems will also need to be managed to prevent system instability. Relative to traditional power flow technologies, advanced power routers can be simpler, more compact and scalable, more responsive, and can find applications in transmission networks as well as in distribution and sub-transmission grids.

For some of these advanced technologies, the ability to control power flow is not as extensive as that of FACTS devices or HVDC systems, but their modular configuration and lower cost (e.g., distributed series reactors) may allow several devices to be installed together to achieve the equivalent level of controllability and capacity. Furthermore, their modular nature would enable them to be produced in large volumes at a manufacturing facility instead of entirely in the field, further reducing cost. New approaches to power flow control, such as magnetic amplification, can be leveraged to produce system benefits at low costs. In general, these advanced power routers would have shorter installation lead times than transmission expansion, providing an additional value stream. They are also becoming more important for use in the distribution system to accommodate greater DER penetration and can help reduce the cost of upgrading and expanding distribution assets to meet future needs.

R&D Needs:

- Novel designs and materials that leverage new mechanisms to provide power flow control capabilities, enable routers to be easily moved as grid congestion shifts, and can help lower capital and maintenance costs
- Advanced power electronic circuit designs and associated materials (e.g., magnetics) that allow for high-frequency operation, higher efficiencies, and increases in performance that are robust to lightning strikes, transients, and other surges
- Field validation and evaluation of advanced applications (e.g., reducing loop flows, damping inter-area oscillations, providing black start capabilities, simplifying outage maintenance, and mitigating harmonics) and developing associated use cases
- Improved models, coordination and control algorithms, and technology integration with energy management systems to provide dynamic power flow control capabilities in meshed networks, including directing power flow to adjacent distribution circuits

Objectives:

- System capital costs of \$10–\$40 per kVA
- Impedance control in the range of 10%–20% of power rating
- Response times < 5 milliseconds

2.2.2 Technology 2 – Medium Voltage Direct Current Converters

As the amount of distributed generation and loads grow that are inherently DC, it may be more efficient to develop DC distribution systems. Deployment of MVDC converters at distribution substations or along feeders can reduce system losses (e.g., reduced conversion requirements of inverter-coupled DERs), improve power quality (e.g., decrease voltage fluctuations), and increase reliability. As with HVDC technologies, MVDC can deliver more power over the same power lines and right-of-way compared to AC technologies at the same voltage class. This capability can help increase system capacity to meet growing loads, especially with the potential of mass-market vehicle electrification and DC fast charging. Other applications of MVDC converters is to tie distribution substations together and to facilitate the integration of energy storage systems, providing power routing capabilities and increasing grid resilience in dense urban centers.

One of the unique capabilities of MVDC converters is the ability to decouple the electrical dynamics on both sides of the tie point from one another, limiting the propagation of faults and disturbances. This can be extremely useful to manage the integration and operation of large microgrid systems (i.e., an entire distribution feeder). MVDC converters can also serve as a buffered interface between T&D systems, enabling each to evolve independently and simplifying institutional issues. Applications include precise control over the flow of real and reactive power in both directions and the ability to aggregate ancillary services from distributed energy resources and provide it to wholesale markets.

R&D Needs:

Novel designs and materials for high-power, high-reliability, high-functionality, compact, and low-cost power electronic modules that offer the possibility of integration with energy storage elements, driver circuits, and embedded intelligence

New converter topologies and designs with built-in redundancy to ensure high system reliability, integrated power filters, and other forms of protection to withstand lightning, fault currents, transients, and surges from other system operations

Thermal management systems (e.g., air, water, and inductive cooling) and packaging to address high energy densities designs and modules, including solutions required for extracting heat from high frequency magnetic cores

Reliable fault detection and interruption capabilities (e.g., low-cost DC breakers), fault tolerant configurations, and coordinated protection and controls between all DC nodes and MVDC zones

Field validation and evaluation of capabilities and advanced applications (e.g., asynchronous operation and seamless connect-disconnect of microgrids, harmonic mitigation, and autonomous reactive power and voltage support) and development of associated use cases

Objectives:
Installed system costs < $100 per kVA
Efficiency > 99% at all levels of loading
Half the footprint of a converter station built with conventional converter technologies

2.3 Advanced Components

Materials and their physical properties are fundamental to the performance of all T&D grid components. Properties such as electrical conductivity, dielectric strength, mechanical strength, thermal conductivity, magnetic permeability, and switching speeds of materials either enable component capabilities or limit their design. In light of the power system trends and challenges discussed in Section 1.1, advanced components will be necessary to overcome fundamental limitations imposed by existing materials. Simultaneously, material innovations developed for other sectors can be leveraged to address some of the challenges associated with current T&D components. Some new functions and enhancements possible with advanced components include self-healing capabilities, added strength, increased lifetimes, smaller sizes, lighter weight, higher power density, and environmental sustainability.

There are four technologies identified for advanced components: (1) dielectrics and insulators, (2) magnetics, (3) electrical conductors, and (4) semiconductor devices.

BENEFITS AND OPPORTUNITIES:

- Reduces the environmental and safety risks posed by transformer or circuit breaker failures
- Increases the power carrying capabilities of underground cables and overhead conductors
- Enables T&D grid components based on power electronics to be smaller, lighter, and more energy efficient
- Improves the lifetime, durability, and reliability of T&D grid components

CHALLENGES:

- Incorporating new materials into T&D grid components will require a focused effort on understanding manufacturing processes.
- New materials will need to perform better and cost less than conventional materials used in T&D grid components today.
- Developing some of the desired functions will require major advances in material science and underlying physics.

2.3.1 Technology 1 – Dielectrics and Insulators

Dielectrics and insulators are material components used to ensure a large voltage can be sustained with an asset without shorting. Insulators are used in shielded cables, bushings, transformers, and circuit breakers to prevent or limit electrical breakdown under high voltages, while dielectrics are used in capacitors which are needed in power electronic systems. There is a wide range of dielectrics and insulating materials, including polymers (e.g., cross-linked polyethylene insulation [XLPE] and silicon rubber), ceramics (e.g., alumina and steatite), fluids (e.g., oil and liquid nitrogen), and gases (e.g., SF_6, air, and halogens).

The safe and reliable delivery of electric power depends critically upon the performance of insulators. Desired properties include high dielectric strength to withstand high voltages and strong fields with minimal partial discharge, high electrical and tracking resistance to minimize leakage currents, ability to withstand high temperatures to minimize degradation during operations, high thermal conductivity to extract heat from components, and self-healing capabilities to extend lifetimes and increase reliability.

R&D Needs:

- Development of low-cost, high-durability, self-healing, and high-temperature dielectric materials for use in capacitors that can withstand high switching frequencies and rapid transients
- Development of low-cost, high dielectric strength, self-healing, thermally conductive, and moisture-resistant insulation for shielded cables that can be easily extruded
- New materials for transformer bushings and surge arresters that last longer, are self-healing, and do not fail catastrophically upon damage
- Advanced manufacturing and synthesis methods of bulk and film-based dielectrics and insulators, including deposition and roll-to-roll processing
- Cost reductions for environmentally friendly alternatives to SF_6 and inorganic transformer oil, such as ester fluids and g^3

Objectives:

- Dielectric strength of > 120 kV/cm at the same price as conventional materials
- Dielectric loss angle (tan delta) of < 0.05% at 60 hertz (Hz) at upper limit of operating conditions
- Enhanced material properties remain stable over useful life of assets (e.g., 20–40 years)
- Temperature withstand > 130°C in continuous operation, > 180°C in emergency situations

2.3.2 Technology 2 – Magnetics

Magnetics are used to couple and convert energy between electric and magnetic fields and are critical to the operation of transformers, inductors, and components based on power electronics. Industrial magnetic materials are typically iron-based and include silicon steel, soft ferrite, soft iron, bulk metallic alloys (e.g., nickel-iron and iron cobalt), amorphous alloys, and nano-composites, and can sometimes contain rare-earth elements.

Efficient and high-quality power conversion, whether between voltages or between currents, depends on the performance of magnetic components. Desired properties include high permeability depending on application, high saturation points to increase energy density and power ratings, low coercivity and high resistivity to reduce hysteretic and conduction losses, good performance at high frequencies to reduce size and weight, high strength and ductility to increase reliability, high Curie temperatures to accommodate high-temperature operations, and earth-abundant content for low costs.

R&D Needs:

Improvement in the properties (e.g., permeability and resistivity) of transformer core materials (e.g., magnetic steel and amorphous alloys) to lower hysteretic and eddy current losses while ensuring ductility and high flux density for compact and reliable designs

Novel materials such as amorphous alloys, exchange-coupled soft and hard magnets, and nano-composites suitable for use with wide-bandgap (WBG) semiconductors that can offer low losses at high-power (e.g., multi megawatt) and high-frequency (e.g., 10–100 kHz) operation

Advancements in metal matrix or hybrid composites to enable tunable properties such as energy density, improved corrosion resistance, usable temperature range, strength, ductility, and permeability along with high manufacturability

Materials and coatings that will enhance the performance of magnetic materials such as flux loss, thermal management, and stability of magnetic properties

Novel materials and designs that leverage advanced manufacturing techniques and other innovative processes to reduce undesirable parasitic parameters, utilize unconventional geometries, enhanced magnetic properties, and enable more compact components

Objectives:

Fifty percent reduction in energy losses for line frequency transformers compared to silicon steel at the same flux density

Fifty percent reduction in eddy current losses for high power (kW to MW) and high frequency (10–100 kHz) transformers compared to state-of-the art materials

Costs comparable to materials used today

2.3.3 Technology 3 – Electrical Conductors

Electrical conductors are used to carry electrical currents and contain electric fields, preventing them from going where they should not. Electrical conductors used in the grid are primarily made from copper, aluminum, and steel, but other more exotic materials, such as high-temperature superconductors, carbon nano-tubes, graphene, and nano-composites, are finding applications. While industrial metals are ubiquitous in the construction of T&D grid components, providing mechanical strength, electrical shielding, and magnetic coupling, their current carrying capability is critical for high-performance T&D lines, bus bars, and transformer windings.

The efficient, reliable, and secure delivery of electricity depends on the combined performance of electrical conductors. Desired properties include low resistance to reduce electricity losses, high mechanical strength to increase reliability, high thermal conductivity to extract heat, high melting points to maintain high strength during operation, high ductility for increased mechanical flexibility and robustness, and earth-abundant content for low costs.

R&D Needs:

Material innovations that can lower the resistance of overhead conductors, shielded underground cables, and transformer windings without degrading other essential properties, such as thermal ratings, mechanical strength, and weight

Materials and coatings that can enhance the performance of electrical conductors depending on application, such as self-cleaning, self-healing, improved cooling, corrosion resistant, fault current-limiting, and super-hydrophobicity

Manufacturing advancements and material improvement for low-cost, high-temperature superconducting wire and associated systems, such as cryogenic systems

Material innovations to improve structural strength and thermal conductivity of electrical conductors for use in component housing to enable more compact and power-dense solutions

Objectives:

Electric conductivity 50% better compared to copper or aluminum

Mechanical strength and thermal conductivity 25% better compared to copper or aluminum

Costs comparable to copper or aluminum

2.3.4 Technology 4 – Semiconductor Devices

Semiconductors are materials that can be used to actively control the flow of electrons and can be thought of as a faster, smoother alternative to an electro-mechanical switch. Semiconductor devices (e.g., transistors, thyristors, and diodes) made from these materials are critical to the operation of T&D grid components such as FACTS, HVDC, and new technologies based on power electronics. The dominant semiconductor used today is silicon, but newer materials with better performance, such as silicon carbide, gallium nitride, and diamond, are being adopted at lower power levels. In addition, there are several other "ultra" WBG semiconductors (e.g., aluminum nitride and gallium oxide) that are topics of current research.

Efficient, high-quality power conversion (i.e., AC to AC, AC to DC, DC to AC, and DC to DC) and fast, precise power flow control depend on the performance of semiconductor devices. Desired properties include high resistance in the off-state and low resistance in the on-state to enable high-power, low-loss operations; high thermal conductivity to operate at high temperatures; high switching frequencies for more precise control and smaller size and weight; low defects for high reliability; and earth-abundant content and easy manufacturability for low costs.

R&D Needs:

Development of low-cost semiconductor devices using new materials (e.g., WBG semiconductors) that have high thermal conductivity, high breakdown voltage, high current carrying capabilities, and the ability to switch at high frequencies

Advances in the growth, manufacturing, and processing (e.g., doping) of WBG semiconductor substrates to ensure high reliability, high repeatability, low defects, and low costs

Innovations in packaging and materials to withstand high-voltage, high-frequency, and high power density device operation to derive the full benefit of using advanced semiconductor materials while maintaining high reliability

Objectives:

Packaged diodes and transistors that cost < $0.10/Amp at 1,200 V

Packaged diodes and transistors that can block > 5 kV and carry > 20 A

Packaged transistors with switching frequencies up to 100 kHz and low losses

2.4 Enhanced Monitoring

Today's grid is a complex and expansive electrical machine consisting of tens of millions of components and technologies that must work reliably together. Most of the physical infrastructure do not possess the capability to provide their status to system operators, so engineering estimates and routine inspections are used to ensure their performance. This paradigm will not suffice for a future grid that is expected to be flexible and adaptable to wide fluctuations from power supplies and dynamic operations with bi-directional power flows. It will also be extremely difficult to reconfigure the system in real-time to mitigate the impact of disruptions and facilitate the recovery from natural and man-made events.

Safe, reliable, and efficient operation and management of the future grid will require high fidelity sensors and intelligence incorporated into T&D grid components to provide actionable information on their condition and environment. Enhanced monitoring will equip components with data analysis and decision-making capabilities that will complement the advances made with the "smart grid" and impart distributed intelligence to the electrical infrastructure.

The three technologies identified for enhanced monitoring are: (1) sensing elements, (2) integrated data processing and communications, and (3) analytics and applications.

2.4.1 Technology 1 – Sensing Elements

Sensing elements (e.g., transducers) may be embedded into grid components as an integral part of the equipment, or they may be used in self-contained packages that are distributed as part of a sensor network over wide areas. Various electrical parameters such as voltage, current, frequency, and phase can be measured to provide information on grid conditions, facilitating operations and protection, while other parameters such as temperature, dissolved gases, moisture, mechanical stress, pressure, and magnetic field are more useful for in-situ health monitoring, prognostic, and asset management purposes.

BENEFITS AND OPPORTUNITIES:

- Enables situational awareness of T&D grid component status to optimize operations during normal conditions and to accelerate restoration during emergency conditions
- Enables T&D grid component health monitoring for condition-based maintenance, lowering lifecycle costs
- Provides a platform for localized and distributed intelligence, enabling more dynamic and adaptive protection settings to increase reliability

CHALLENGES:

- Developing the correct sensor capability will require a detailed understanding of the system parameters of interest
- Ensuring the security, quality, and timeliness of data will require an integrated sensing and communications strategy
- The business case and value proposition of using many more sensors will need to be analyzed and integrated into operations

While a large number of physical and electrical properties may be measured, the type and frequency of data to be collected will depend on the specific component and the purpose of the information gathered. Development of advanced sensor technologies will require consideration of several factors, including adaptability to changing grid conditions, cost versus benefits, the sensing environment, precision and sensitivity, selectivity, measurement latency, versatility, durability, and reliability. For ubiquitous sensors, low costs and ease of integration or installation will also be important design considerations.

R&D Needs:

Testing and modeling to improve understanding of the underlying causes of component degradation so that leading indicators of failure may be identified and measured, including component level monitoring for correlation of impacts

Materials and sensing elements that provide high accuracy and will function reliably under harsh operating conditions, such as high voltages and currents, extreme temperatures and pressure, high and varying electric and magnetic fields, volatile and corrosive fluids, high saline-content, and humid atmosphere

High-bandwidth, low-latency, and high-selectivity sensing elements (e.g., optical sensor for voltage and current) for advanced applications, including broad-spectrum data capture during highly transient events and the detection of low current fault conditions

Novel designs, packaging, and manufacturing (e.g., basic impulse insulation requirements) to ensure performance, reliability, durability, and low cost of sensors, including non-contact/remote sensing options to facilitate installation and operation with legacy equipment

Objectives:

Accuracy better than 1% of critical value of interest

Capital cost < $1 per sensing element for ubiquitous sensors

Sensor capital cost and lifetime commensurate with instrumented equipment and application

2.4.2 Technology 2 – Integrated Data Processing and Communications

Sensing elements must be integrated with power supplies, communications, and other subsystems to operate as planned and deliver useful information to system operators and asset owners. The cost associated with these data and communication systems, their latency and bandwidth, data storage capacity, reliability, and security must be considered within the broader framework of power system operations and planning. With the large number of sensors anticipated in the future grid that are widely dispersed and located in remote areas, the ease of installation, commissioning, servicing, and updating these systems will be important design considerations. Automation and secure, wireless communication connectivity will be important attributes of future sensor technologies to help reduce labor and maintenance costs.

Further integration of sensors with onboard computing and data processing can provide local analysis and decision-making capabilities, transforming T&D grid components with these sensors into "smart" assets. "Smart" assets have the potential for distributed intelligence that can work individually and collectively to adapt to changing grid conditions and self-regulate against imminent failures. Embedded intelligence can further expand "smart grid" capabilities by allowing T&D components to self-adjust their protection settings to cope with varying fault levels and to auto-reconfigure local protection zones to mitigate against wide-area disruptions. These integrated processing and communications platforms should be standardized, where appropriate, to encourage innovation and interoperability and to minimize vendor "lock-in."

R&D Needs:

Novel communications and data processing architectures (e.g., hierarchical and fractal) that support more distributed intelligence and are scalable to manage a large number of sensors, flexible to accommodate new data sources and applications, and able to leverage multiple modes of communication, including peer-to-peer and meshed

Integration of low-cost, robust, low-latency, and secure onboard communication capabilities (e.g., radio frequency, Wi-Fi, cellular, and satellite); onboard computing power; data storage; and development of appropriate control algorithms to enable plug-and-play features, auto-commissioning, self-diagnosis, self-regulation, and automatic updates over wireless communications

Algorithms for embedded intelligence, including the ability to adapt performance based on grid conditions (e.g., gather data more quickly even if its accuracy and precision suffers slightly) and to exploit knowledge of physics, location, topology, and other sensors to self-calibrate and validate data

Computing and communication platform solutions that have a standardized language and interface (e.g., Linux) to enable application innovation, including allowing porting of new applications (e.g., data compression for fast communication) as they are developed

Integration of auxiliary systems such as measures to ensure data trustworthiness (e.g., low-cost timing chips and anti-spoofing Global Positioning System locators) and low-cost power harvesting and storage capabilities needed for back-up and remote sensors

Objectives:

Installed costs < $100 per sensor system

Installed costs < $10,000 per instrumented grid node (e.g., substation and facility)

Support up to 10,000 nodes without performance degradation

Communication latency < 1 millisecond within 10 miles

2.4.3 Technology 3 – Analytics and Applications

Sensor data about T&D grid components is of low value unless it can be transformed into actionable intelligence. Analytical tools, algorithms, controls, and protection schemes are the technologies needed to translate these new data streams into high-value applications. These applications can be integrated into energy management systems to ensure the efficient, reliable, flexible, and adaptable operation of the future grid. Some capabilities include recovering from abnormal events, rapidly adjusting controls to maintain peak efficiency, reacting to disruptions to maintain stability, improving power quality, and cancelling nuisance harmonics.

Condition-based maintenance and asset replacement strategies are an application area that can be significantly improved with enhanced monitoring. As T&D components age, analytics will become increasing important for the management of these assets, especially approaches based on better understanding of failure modes and component degradation to optimize investment choices. Additionally, there is a lot of value that can be extracted from existing sensing and measurement infrastructure, especially at the distribution system, which has traditionally been limited to substation monitoring and control. Limited resources can be better allocated through knowledge-based management of T&D grid components and asset utilization can be maximized through real-time dynamic control.

Another application area that can be revolutionized is component and grid protection. For example, traditional distribution protection schemes were developed based on passive radial configurations with non-directional over-current relaying. With increasing amounts of distributed energy resources and power flow control technologies, the directionality of currents under normal and fault conditions raises concerns with safe operations due to possible loss of protection coordination and misoperation. Fault contributions from inverter-based distributed generation are much smaller than traditional synchronous generation due to low inertia and current limiting associated with power electronics. These smaller fault currents may prevent fuses and circuit breakers from operating, limiting proper coordination with other protection devices. Next-generation protection equipment with enhanced monitoring can address this concern.

R&D Needs:

Robust technical and economic data for decision support tools (e.g., asset management), including maintenance options, operating and maintenance costs, available monitoring technologies, equipment capital costs, performance metrics, and degradation mechanism for different components and systems

Standardized and secure database structures, terminology, and definitions for information relevant to a wide range of applications (e.g., asset management analytics) such as asset registry, location, and history, including inspection, maintenance, operating, and event

Tools and algorithms to assess component health, predict future performance, and estimate remaining life, helping to determine, rank, and prioritize appropriate actions (e.g., perform maintenance, refurbish, purchase spare, replace, or upgrade) drawing on information from embedded sensors and other data sources (e.g., databases and weather forecasts)

New protection, coordination, and control algorithms for setting-less protection based on embedded sensors and other data sources, enabling more adaptive and dynamic capabilities that respond to changing network conditions, power flows, loads, and generation sources, including situations with islanding of microgrids and utilization of DERs

Leveraging advances in machine learning and artificial intelligence to mine available data sources to improve algorithms, tools, and applications, including forensics, diagnostics, and prognostic condition-based maintenance, preventive- and recovery-based assets management, and vulnerability assessments

Development and assessment of use cases such as real-time condition monitoring of large power transformers, other substation equipment, and underground cables for early failure prediction and diagnostics

Objectives:

Autonomous adjustment and control to prevent unwanted events in < 5 milliseconds

Better than 99% success rates in the detection of and the protection against targeted events

Improved analytics result in > 5% savings in asset management on average

2.5 Supporting Activities and Issues

In addition to the various application areas and technologies identified, there are a range of supporting activities and issues that require consideration and attention to achieve broader adoption of innovations. Many of these supporting activities are associated with the integration of new technologies into the broader power system and industry acceptance, including addressing institutional changes. Efforts in these supporting activities—in coordination and partnership with relevant stakeholders across government, academia, and industry—will help to accelerate reaching technology objectives, facilitate their integration into operations and planning, and inform investment decisions to realize benefits cost-effectively.

These activities and issues are organized into five key categories: (1) testing and model validation; (2) simulations and analyses; (3) architectures, interoperability, and standards; (4) manufacturing and supply chain; and (5) education and training, and are discussed in more detail below

2.5.1 Testing and Model Validation

Testing and experimentation is a critical part of the technology development process and is necessary to assess the merit of new ideas, evaluate performance, and better understand physical phenomena. Because field validation of advanced T&D grid components can be expensive and risky, small-scale testing and modeling is often used to predict performance and issues prior to system scale-up. While computational capabilities have advanced to support more complex modeling activities, the results are only as good as the underlying model. The combination of testing and model validation must be conducted hand-in-hand to build confidence in the new technology, which will help accelerate its development.

Validated models that produce realistic results with high confidence are needed before industry will integrate new T&D grid component technologies, especially those based on power electronics, into their operating and control systems. Accurate component models are also useful to evaluate the performance and value of new capabilities in planning tools. Ensuring that there are adequate testing capabilities, proper test procedures, realistic use cases, and system models will be important for these activities. For example, testing capabilities that can simulate GMDs, EMPs, and cyber attacks are needed to help identify vulnerabilities from these threats and inform new design requirements that can mitigate impacts.

2.5.2 Simulations and Analyses

Simulation and analysis are important activities that can support the broader adoption of new T&D grid component technologies. Outcomes and results from analyses can be used to answer key questions that industry has regarding the viability and value of a new technology, such as contributions to resiliency and system upgrades and the impacts of dynamic interactions between power electronic devices and systems. These analyses are needed to assess value (e.g., cost-benefits), evaluate design trade-offs (e.g., lifecycle costs), and understand capabilities or limitations (e.g., efficiency gains from a DC paradigm versus reliability concerns) of adopting new technologies.

In support of these analyses, simulation tools that leverage validated models and can assess various factors (e.g., technical, market, and policy) over a wide range of time-scales (i.e., milliseconds to years) will be needed. A thorough evaluation of the potential costs and benefits of deploying new component technologies at scale will require modeling and simulation of the economic and operational impacts of the technologies within a large-scale power system model. These analyses may include production cost modeling, power flow, dynamic stability, and potentially even time-domain transient simulations.

2.5.3 Architecture, Interoperability, and Standards

In support of grid modernization efforts, grid architectures are being analyzed, evaluated, and changed to enable new operational paradigms. These architectures help to define interoperability requirements that feed into the development of associated standards and new best practices. To ensure the long-term success of new T&D grid components and to facilitate their integration, it is important to engage and align with architecture, interoperability, and standards efforts early and frequently. Participation in grid architecture processes and standards development can help to lower market and regulatory barriers, ensuring that new paradigms and standards will incorporate and consider the enhanced capabilities and features (e.g., modularity, scalability, and faster response times) available with new technologies.

2.5.4 Manufacturing and Supply Chain

The impact of manufacturing processes and supply chains are important to the success of new T&D grid components, especially if they involve new design architectures or new materials. Ease of manufacturing, transportation, assembly, and process scalability need to be considered in technology R&D to help address concerns with cost. Additionally, manufacturing processes directly affect the physical properties of materials and will need to be precisely controlled to effectively incorporate advanced components into next-generation T&D grid hardware technologies. Innovations in manufacturing techniques, such as roll-to-roll printing and additive manufacturing, can also be leveraged to enable the production of new designs not achievable with conventional processes.

To ensure the security, integrity, and interoperability of new T&D grid components, supply chains and performance validation associated with the underlying materials, subcomponents, and systems will require attention. Attention to these issues is important to mitigating vulnerabilities to cyber attacks, especially with new technologies that have greater use of sensors and embedded intelligence, as well as vulnerabilities to supply shocks. Evaluation of supply chain issues, acceptance testing, and compliance testing can help to address some of these concerns, encourage greater sustainability in manufacturing, and promote U.S. competitiveness.

2.5.5 Education and Training

The U.S. electric utility industry relies on thousands of skilled and educated workers to maintain and support the T&D systems. Education and training programs are needed to prepare future engineers, provide a steady stream of innovations, and build a strong pipeline of energy sector workers who will help modernize and secure the grid, especially with the introduction of new T&D grid components.

As many of the most experienced systems operators, planners, and linemen begin to retire, there is a very high risk that the institutional knowledge these workers possess will be lost, and therefore dedicated knowledge and skill transfer programs are needed to ensure continuity of operations. Additionally, as new T&D grid components become increasingly automated and complex, IT, security, material science, and manufacturing will become valuable backgrounds for new system operators, planner, and engineers. Interdisciplinary research programs and university curricula will be needed to address these emerging requirements.

2.6 Portfolio Synergies

The various activities associated with each technology introduced above can provide value to industry individually, but a coordinated approach ensures that synergies can be identified for complementary benefits and to help overcome challenges. Research and institutional activities for a technology within a focus area can help advance other technologies within the same focus area through adopting best practices and lessons learned, and through leveraging technical progress. Other activities are cross-cutting and can support a range of technologies across multiple focus areas.

2.6.1 R&D Focus Areas

The TRAC Program has three primary R&D focus areas that drive advancements in the application areas and technologies introduced above to help meet program goals and objectives. These focus areas are:

- **Power Electronics** – Application of power electronics in the next-generation of T&D grid components is a fundamental game changer. Advancements will allow the grid to move from slow, electro-mechanical controls to one based on fast, dynamic controls. Unique challenges include the high voltage, high power, and high reliability requirements associated with their integration. This focus area underpins the advanced transformers and low-cost power flow controller application areas.
- **Materials** – Materials often dictate the cost and performance of T&D grid components. Advancements in material science, nanotechnology, modeling, characterization, and manufacturing processes can be leveraged to expand the fundamental limits and possibilities (e.g., geometries, physical properties, capabilities) of next-generation designs. This focus area underpins the advanced components application area.
- **Sensors** – Sensors are critical for determining the operational state and health of grid hardware technologies and underlying components. Advancements coupled with computational capabilities, communications, and analytics can provide localized intelligence and enable connectivity of next-generation T&D grid components to improve performance and situational awareness. This focus area underpins the enhanced monitoring application area.

2.6.2 Technology Linkages

Figure 3 shows the linkages between the three R&D focus areas and associated technologies within the TRAC Program portfolio, their anticipated utilization within the grid (i.e., transmission versus distribution), and the relative timing (i.e., near-, mid-, long-term) of technology maturation assuming sufficient resources are available. The technologies associated with the materials and sensors R&D focus areas are cross-cutting and are not highlighted for simplicity.

In the long-term, SSPS will be a critical technology that has application in both transmission and distribution systems. Ultimately envisioned as a system consisting of modular, scalable, flexible, and adaptable power blocks that can be used within all substation applications, SSPS converters will serve as power routers or hubs that have the capability to electrically isolate system components and provide bidirectional AC or DC power flow control from one or more sources to one or more loads—agnostic to magnitude and frequency. Research for technologies in the near-term and mid-term can inform and accelerate advancement of SSPS.

For example, advanced power routers and power electronics (PE) augmented distribution transformer rely on improved power electronic devices and distributed controls that can help establish high-value use cases for SSPS and increase utility comfort with adopting these advanced technologies. Meanwhile, development of flexible and adaptable LPTs and MVDC converters can help improve the material properties required for high voltage operations and establish modular architectures and configurations needed in SSPS to make them scalable.

Aside from the synergies within and across the TRAC program R&D focus areas, there are opportunities and benefits that span into other technology sectors. For example, advancement in high voltage power electronics can be used in battery energy storage systems, fuel cells, and solar inverters. Simultaneously, advances in these sectors can be leveraged for the TRAC program. Additionally, progress made in the materials focus area (e.g., insulators and dielectrics, magnetics, conductors, and semiconductor devices) and sensors focus area (e.g., sensing elements, communications, and analytics) have broad applicability and can be synergistic with a number of other technology sectors.

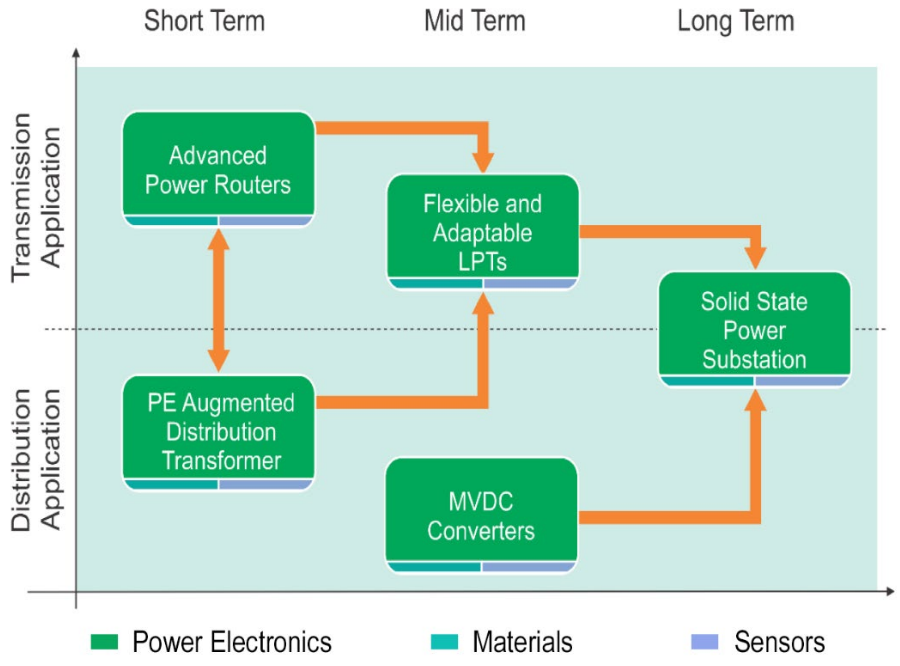


Figure 3. TRAC Portfolio Synergies

3. PROGRAM EXECUTION

This Vision and Framework document will be used to guide on-going projects and the development of the TRAC program portfolio moving forward. It is anticipated that quadrennial updates will be necessary to reflect research progress, changing priority needs, and the state of the power system as it evolves. Implementation schedules, annual operating plans, and the timing of outcomes for the activities described in this document will depend on the program budget and annual appropriations.

The challenges associated with the TRAC program goals are broad, and the objectives and specific activities for each application area or technology will require refinement through the development of detailed technical roadmaps to supplement this document. These roadmaps will be formulated with extensive involvement of relevant stakeholders, input from subject matter experts, and consideration of the unique role of the Office of Electricity (OE).

In pursuit of the vision and goals laid out in this document, several practices will be followed to ensure the success and beneficial impact of program activities. The following practices are integral to guarantee that the TRAC program effectively serves industry, the public, and government:

- Active project management
- Broad program communication
- Continuous portfolio improvement
- Diverse stakeholder engagement

3.1 Active Project Management

Research and development (R&D) topic development, execution, and project management processes for TRAC are designed to ensure that all funded projects in the program portfolio are chosen based on their qualifications in meeting clearly defined objectives and performance targets in support of TRAC program goals.

Most TRAC R&D activities are supported with funding to the National Laboratories and financial assistance to industry and academia made through a competitive process. Competitive solicitations, including use of the Small Business Innovation Research/Small Business Technology Transfer[21] program and the Technology Commercialization Fund,[22] ensure that awards are given based on merit and result in better project outcomes. These funding opportunity announcements (FOAs) articulate the needs, objectives, and requirements for a particular topic area. After proposals are received, a merit review is conducted with a thorough, consistent, and independent examination of applications based on pre-established criteria in

---

[21] Small Business Innovation Research–Small Business Technology Transfer, “About STTR,” https://www.sbir.gov/about/about-sttr.

[22] U.S. Department of Energy, Office of Technology Transfer, “Technology Commercialization Fund,” http://energy.gov/technologytransitions/technology-commercialization-fund.

the FOA. Independent technical experts are recruited to critically review project proposals and provide a basis for project selection.

Once an R&D project is funded, stage-gate reviews are used to evaluate progress and to determine whether the project is ready to advance to its next phase of research, whether it needs to pursue alternative paths, or whether it needs to be terminated. It is a useful tool that establishes quantitative technical performance goals for multi-year projects with built-in decision steps and systematic monitoring and evaluation of technical progress at each project stage to manage risks. In addition to effective communications with the project team and periodic site visits, these reviews help to promote project progression and success.

3.2 Broad Program Communication

Outreach and educational activities are essential to meeting TRAC program objectives, as they keep industry, policymakers, and consumer groups across the Nation informed and up-to-date regarding effective strategies, technologies, tools, and techniques developed in the TRAC program portfolio. Robust communications with diverse stakeholder groups through a variety of outreach products and delivery channels (e.g., fact sheets, journal articles, published reports, Internet presence, and training courses) will increase awareness of program outcomes and articulate the potential value of R&D projects. Broad communication efforts can facilitate industry implementation of new measures, help inform development of appropriate incentives for policymakers, and enable consumers to understand how TRAC program activities impact their lives.

3.3 Continuous Portfolio Improvement

The TRAC program portfolio is coordinated to maximize benefits from interrelated activities. While each technology can provide value to the industry individually, a coordinated portfolio approach will amplify results and leverage synergies. As the power system evolves, peer reviews will be used to assess the portfolio and improve the program to ensure projects continue to provide value. Peer reviews are conducted every two years to evaluate activities based on scientific merit, likelihood of technical success, actual or anticipated results, and effectiveness of research management. Results from the evaluation will feed back into program planning and portfolio management.

For each review, a panel is selected that is composed of a broad and balanced spectrum of expertise and perspectives. The reviewers evaluate each project against pre-established criteria, including the projects' quality, productivity, and accomplishments; the projects' relevance to OE and DOE's mission; and the projects' management. The projects' impact on R&D goals, the industry, and policies are also frequently considered. In addition to specific projects, reviewers also assess the program overall and provide input on strengths, weaknesses, and specific changes that would improve the program portfolio. This process helps guide research directions, assess progress, and if necessary, redirect resources toward the most promising technology pathways. Peer reviews also provide a forum for interested parties to learn about the TRAC program status and future plans.

3.4 Diverse Stakeholder Engagement

Engaging diverse stakeholders throughout the R&D process is critically important. Active engagement, potentially with dedicated point-of-contacts at stakeholder groups and organizations, is essential to establishing and reinforcing strong working relationships with all organizations involved in the research, development, manufacturing, and use of transmission and distribution grid components. Effective public–private partnerships are a key strategy to enable the TRAC program to implement its R&D plans and achieve its goals. Additionally, two-way information sharing helps to minimize duplication of efforts and maximize the efficiency of resource allocation.

Drawing on the expertise, resources, and perspectives of all facets of the sector ensures that grid hardware needs are anticipated from every angle and are met as quickly and effectively as possible. The likelihood of success in addressing technical barriers and achieving products and services of commercial value is enhanced when National Laboratories, academia, industry, vendors, asset owners and operators, and other government agencies work with the TRAC program to accomplish the following:

- Identify common goals, challenges, needs, and pathways for technology development
- Share the costs of technology research and development projects
- Increase outreach and awareness of available and developing technologies
- Evaluate the progress of R&D projects and research areas
- Identify gaps in R&D and opportunities to leverage resources
- Gain mutual understanding of roles and responsibilities in achieving goals

Moving forward, stakeholder engagement and partnerships will be important to ensure a smooth path to adoption of technologies and tools supported by the TRAC program. Possible topic areas and activities for collaboration are shown below in Table 3.

Table 3. Possible Areas of Collaboration for TRAC Program Activities

Partner	Areas of Collaboration
Utility Industry	• Providing field validation sites • Conducting R&D (e.g., Electric Power Research Institute and National Rural Electric Cooperative Association) • Developing standards and promoting interoperability • Conducting workforce development and training • Collecting and sharing component data • Defining performance requirements

Partner	Areas of Collaboration
Equipment Vendors	• Conducting R&D • Sharing testing capabilities • Developing and validating models • Improving manufacturing and supply chains • Sharing performance data
Academia	• Conducting workforce development and training • Conducting R&D
National Laboratories	• Modeling and testing components • Conducting R&D • Conducting computational modeling and analysis
DOE – Office of Science	• Conducting fundamental material science and characterization ○ Basic Energy Sciences (e.g., Materials Science and Engineering Division, Energy Frontiers Research Centers) • Researching advanced computing for modeling ○ Advanced Scientific Research and Computing
DOE – Office of Energy Efficiency and Renewable Energy	• Developing materials research and manufacturing techniques ○ PowerAmerica Manufacturing Innovation Institute ○ Institute for Advanced Composites Manufacturing Innovation ○ American Makes: National Additive Manufacturing Innovation Institute • Determining lifecycle cost estimates and evaluating supply chains

Partner	Areas of Collaboration
DOE – Advanced Research Projects Agency-Energy	• Conducting materials research for grid applications ○ Strategies for Wide-Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES) ○ Agile Delivery of Electrical Power Technology (ADEPT) ○ Power Nitride Doping Innovation Offers Devices Enabling SWITCHES (PNDIODES) • Conducting grid components R&D ○ Green Electricity Network Integration (GENI) ○ Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS) ○ Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely (BREAKERS)
U.S. Department of Homeland Security	• Defining risks from physical and cyber threats • Defining emergency response and recovery requirements
U.S. Department of Defense	• Conducting grid components R&D (e.g., electric ships) • Sharing testing capabilities (e.g., electromagnetic pulses [EMP] characterization) • Providing field validation sites

ABBREVIATIONS

A	amp
AC	alternating current
DC	direct current
DER	distributed energy resource
EMP	electromagnetic pulse
FACTS	flexible alternating current transmission system
FCL	fault current limiter
g3	green gas for grid
GMD	geomagnetic disturbance
HTS	high-temperature superconductor
HVDC	high-voltage direct current
Hz	hertz
ICT	information and communication technology
IT	information technology
kHz	kilohertz
kV	kilovolt
kVA	kilovolt-ampere
LPT	large power transformer
MVA	megavolt-ampere
MVDC	medium-voltage direct current
R&D	research and development
SF6	sulfur hexafluoride
SSPS	solid state power substation
STATCOM	static synchronous compensator
SVC	static VAR compensator
T&D	transmission and distribution
VAR	volt-amp reactive
WBG	wide-band gap

APPENDIX—TECHNICAL NEEDS, REQUIREMENTS, AND OPPORTUNITIES

In light of the various trends and challenges affecting the electric power system, there are several desired functions and requirements for next-generation T&D components. Technology gaps and opportunities for the various grid component categories within the TRAC program scope are summarized below.

Transformers

- More flexible and adaptable LPTs that will facilitate transformer sharing in emergency situations, reducing the variety of LPTs required in a utility's footprint and decreasing the cost of manufacturing such LPTs from economy of scale. These designs should maintain high efficiencies, have variable impedances, accommodate various high-side and low-side voltages, be easy to transport and install, and be cost-effective compared to traditional LPTs serving as permanent replacements.
- Broader use of single-phase transformers that are more compact than what is available today can increase grid resilience. Design innovations, such as more robust high-voltage bushings and stronger, standardized bushing cavities that make failed bushings easy to remove and replace, will also help to increase resilience.
- New distribution transformer designs and materials are needed to meet new efficiency standards and to increase environmental friendliness. Higher efficiency at all levels of loading and overloading can benefit from utilizing high conductivity conductors in continually transposed arrangements to achieve low stray and eddy current losses.
- Power electronics augmented and other novel hybrid distribution transformer solutions can provide new functionalities such as altering short circuit impedances, harmonic filtering, and interfacing with DC systems to improve efficiency.
- SSTs can be utilized in strategic locations to provide enhanced functionality and flexibility to help control non-steady state power sources. For instance, a SST can perform voltage regulation, supply reactive power, and be used to form hybrid AC and DC grids. They can also be used to manage the interaction of microgrids with utility systems, regulating the process of disconnecting and reconnecting, quickly and precisely changing the direction and magnitude of power flow, and limiting fault currents.

Table A-1. Transformers Technology Gaps

Technology	Gaps
Large Power Transformers	• Flexible and adaptable designs to promote interchangeability and greater standardization • High-efficiency, long-lifetime, and modular designs to facilitate replacement and reduce transportation costs, transportation duration, and installation time • Novel low-cost soft magnetic materials to reduce the weight, size, and losses in LPT core • Understanding of the physics in electrical steel and other magnetic materials to reduce production complexity and to fine tune properties • Light-weight, low-cost, low-resistance, and low-eddy current conductors to achieve high efficiency at all load levels and to reduce the weight, size, and loss in windings • Reliable cryogenic dielectrics and robust refrigeration systems for superconducting LPTs • Novel high-temperature insulators and insulating structures, design, and manufacturing methods to enhance LPT reliability • Improved shielding and other insulating materials to provide robustness against vacuum and sulfur hexafluoride (SF_6) breaker switching, lightning, and other surges • Low-cost and environmentally-friendly insulating materials • Tools and methods to extend LPT lifetime, including integration of sensors and intelligence
Distribution Transformers	• More flexible and efficient designs that incorporate additional functionalities, sensing, and communication, including the use of power electronics • Novel low-cost, soft magnetic materials to reduce the weight, size, and losses in core • Light-weight, low-cost, low-resistance, and low-eddy current conductors to achieve high efficiency at all load levels and to reduce the weight, size, and loss in windings • Reliable high-temperature insulation to accommodate higher stresses • Improved shielding and other insulating materials to provide robustness against vacuum and SF_6 breaker switching, lightning, and other surges
Solid State Transformer	• Low-cost, high-voltage, high-power, and high-frequency WBG power devices and modules • Novel low-cost soft magnetic materials to reduce loss, size, and weight of high-voltage, high-frequency transformer cores for use with power electronics • Better conductors and insulation materials suited for high-voltage, high-frequency, and high-power applications, including withstanding harmonics • Novel converter topologies with efficient thermal management to expand SST functionalities • Improved shielding and other insulating materials to provide robustness against vacuum and SF_6 breaker switching, lightning, and other surges
All	• Modeling and analysis of component performance to understand their interactions with variable renewables and DERs and the broader impacts on system operations • Better thermal management • Techno-economic analyses of systems to determine value propositions • Low-cost, scalable manufacturing methods and testing of prototypes

Cables and Conductors

- Compared to conventional conductors, High Temperature Low Sag (HTLS) lines can typically carry twice the power under continuous operation, increasing ampacity over existing right-of-ways. However, operating at higher temperatures (from increased currents) also increases resistance and thus losses. Conductors with lower resistivity, better thermal stability, and lighter weight can provide higher efficiency and reliability.
- Underground shielded cables provide improved reliability but typically have higher costs compared to overhead lines (up to 10X) due to installation and maintenance. New trenching methods and improvements in cable costs and capabilities (e.g., lighter weight, high-pressure handling, and embedded diagnostics) can strengthen the value proposition.
- Another option is the use of high temperature superconducting (HTS) underground cables, which have essentially no electrical resistance. However, the use of this technology has been limited because of the high cost of ownership, stemming from the wires, refrigeration system, and additional maintenance.
- Fouling (by salt, dirt, debris, or ice) of insulators that hold overhead conductors can lower their insulating capability resulting in flashovers and line outages. Additionally, the connectors between conductors are they weakest link and can benefit from increased strength and lower contact resistance.

Table A-2. Cables and Conductors Technology Gaps

Technology	Gaps
Overhead Power Lines	• Testing and validation of long-term performance of HTLS conductors through field- and accelerated lifetime testing of factors such as thermal-mechanical stresses, fatigue and corrosion • Low-cost, light-weight, high-ampacity or high-strength conductor materials • Understanding of the mechanisms that lead to performance enhancement in novel conductor materials to guide the development of low-cost, scalable manufacturing processes • Simple and low-cost means to reduce the operational temperature or to increase the thermomechanical strength of overhead lines to maintain reliability and ampacity • Simple and low-cost means to increase strength and prevent icing on overhead line for service reliability
Underground/ High-Voltage Direct Current Cables	• Innovative high-temperature moisture-resistant insulating materials with enhanced stability against aging suitable for high-voltage/extra-high-voltage applications • Low-cost, low AC-loss, high-ampacity superconducting wires or room temperature ultra-high conducting wires • Reliable cryogenic dielectrics and robust refrigeration systems for superconducting applications • Integrated sensors to provide early detection of imminent failures

Technology	Gaps
Connectors	• Low-cost surface treatment to reduce or prevent oxidation of connector-conductor interface • Robust connector design to enhance connector–conductor electrical conductivity and mechanical integrity • Low-cost sensors to monitor structural health and performance of connector–conductor system
All	• Modeling and analysis of component performance, understanding their interactions with variable renewables and DERs, and the broader impacts on system operations • Techno-economic analyses of systems to determine value propositions • Low-cost, scalable manufacturing methods and testing of prototypes

Power Flow and Voltage Controllers

- HVDC links are typically used to send bulk power over long distances, but there are also back-to-back HVDC converter applications to enable power transfers between asynchronous grids (e.g., the U.S. interconnections). These systems can be used to provide synthetic inertia and reduce system congestion if they are operated in a coordinated manner. HVDC converters can also be networked to form a high-voltage backbone, but multi-terminal configurations and adequate protection schemes and equipment (e.g., DC breakers) will be needed.
- DC converter technologies can be deployed in sub-transmission or distribution systems (i.e., medium voltage) to increase energy efficiency, controllability, and resiliency in a future grid with more DC loads, such as electric vehicles, data centers, and inverter-based DERs.
- Mechanical-based technologies such as capacitor banks and reactors provide a coarse level of control to improve power flows and maintain voltages. As more variable renewable resources are deployed, dynamic and granular control capabilities from FACTS devices and the equivalent on the distribution system, known as customer power devices, will become more important.
- Power electronics-based voltage regulators and controllers can quickly correct voltage levels and improve phase imbalances but are susceptible to damage by high currents, such as those encountered under inrush, overload, or short circuit conditions. Isolation and other design enhancements can provide immunity to excessive currents.

Table A-3. Power Flow and Voltage Controllers Technology Gaps

Technology	Gaps
HVDC Converters	• Low-cost, reliable, high-voltage and high-power WBG devices to reduce the cost of converters and expand converter topology options

	• Innovative packaging with thermal management for high-voltage, low-loss, and high harmonic performance and fault blocking capabilities in a compact and low-cost design. • Mixed converter technology (line-commutated converter–voltage source converter) hardware testbeds and vendor-agnostic to understand the dynamic performance of such mixed systems • Standardized, vendor-agnostic multi-terminal HVDC designs that are sufficiently flexible to ensure the ready integration of future DC links • Flexible, intelligent, real-time, and high-resolution DC-AC grid emulator to model the behavior of hybrid AC/DC/microgrids
FACTS Devices	• Low-cost, reliable, high-voltage, high-power WBG devices and new topologies to change design paradigms and lower overall system costs • Designs that enable low-cost manufacturing and economies of scale to reduce costs • Innovative distributed concepts based on novel semiconductor device topologies and control schemes in a low-cost and high-capacity package • Simple tools to optimize the locations, compare the performances, and provide techno-economic analyses of available power control devices
Other Flow Controllers	• Improve the construction materials, system design, and shielding and control schemes of voltage regulators and other custom power devices • Explore new power flow control mechanisms and leverage advances in power electronics
All	• Modeling, analysis, and testing of component performance to understand system impacts and interactions with other components • Better thermal management • Techno-economic analyses of systems • New control theories that can utilize these power flow control capabilities and integrate them into next-generation grid management systems

Protection Equipment and Switchgear

- Hybrid switches and circuit breakers made from the combination of mechanical and solid state devices potentially provide faster interruption capabilities, opening opportunities for dynamic fault coordination.
- For advanced multi-terminal HVDC networks to be realized, reliable HVDC circuit breakers with matching power ratings are needed. In addition, multi-terminal DC networks require advanced methods for DC fault identification and location.
- Superconducting fault current limiters (FCLs) have the unique property of having little to no resistance or impedance in the superconducting state but quickly become resistive at the transition temperature. Power electronics-based FCLs can also be used to insert the desired resistance or impedance during faults.
- Surge arresters with intelligent and dynamic rating capabilities can help facilitate system upgrades and lower costs as new technologies are introduced,

such as power electronics-based equipment, which are much more susceptible to over-voltages.

Table A-4. Protection Equipment and Switchgear Technology Gaps

Technology	Gaps
Circuit Breakers	• Understanding of arc physics to facilitate design innovations to reduce the complexity, improve switching speed, and decrease the footprint of circuit breakers • Innovative designs and testing of fast switching, low-loss, compact, and cost-competitive hybrid and solid state DC breakers with less susceptibility to current chopping and restrikes • Low-cost, reliable, high-voltage, and low-loss WBG devices to enable the development of hybrid and solid state breakers • New materials, designs, and technologies to eliminate or reduce the impact of leaks, such as oil-less compressors and alternatives to SF_6 • Tools and technologies to maintain existing breakers without extensive disassembly, including non-intrusive diagnostics for breaker conditions
Arresters	• Low-cost, reliable, high-performance, and compact arresters for > 1,000 kV applications • Low protection-to-rated voltage arresters that function without allowing too much current through during switching but still have temporary over-voltage capability to survive surges • Novel insulating materials that can self-heal so surge arresters will not fail catastrophically
Fault Current Limiters	• Design and testing of superconducting FCLs at transmission voltages • Innovative solid state and hybrid FCLs that are low-loss, cost competitive, and compact • Low-cost, reliable, high-voltage and low-loss WBG devices to enable the development of solid state and hybrid FCLs
All	• Modeling, analysis, and testing of system performance to understand impacts on grid and other grid components • Techno-economic analyses of systems • Flexible protection schemes that can maintain coordination under bi-directional, variable flow, and variable fault level conditions while maximizing the utilization of existing assets and adapting to new protection technologies

Equipment Sensors and Protection

- Physical limits for grid components and equipment are generally a function of operating conditions, including the ambient environment, which are dynamic. However, electrical loading and power ratings are set to accommodate the full range of conditions that grid assets will experience (e.g., maximum ambient temperature). More accurate equipment sensors enable more optimal operations and asset utilization.
- Use of data from field sensors, asset history, and operating conditions to forecast maintenance needs can reduce utility costs. Condition-based maintenance for each piece of equipment can help schedule maintenance as needed, as opposed to using a fixed interval maintenance schedule.
- Traditional distribution protection schemes were developed based on passive radial networks with no distributed generation or power flow control capabilities. The additional fault currents from greater deployment of distributed resources and their low current contributions raise concerns for the adequacy of existing protection equipment and possible loss of protection coordination. As protection becomes more complex due to two-way power flows, improved sensors and protection schemes will be required to adapt to changing conditions on the grid.

Table A-5. Equipment Sensors and Protection Technology Gaps

Technology	Gaps
Equipment Sensors	• Low-cost, high-bandwidth sensors with high accuracy and communications capabilities that can measure and transmit the parameters of interest • Innovative materials with high sensitivity and selectivity to a range of chemistries and gases • Resilient sensors that have robust and reliable performance under off-normal conditions, including immunity to hazards and disruptions
Interrogation Platforms	• Low-cost, low-latency, and secure communication technologies suited for diverse sensor applications. • Data and communications architecture that supports significant increases in the number of sensors across the grid and more distributed intelligence
Algorithms and Applications	• Leveraging advances in machine learning and artificial intelligence to improve tools and algorithms associated with asset monitoring, protection, and other applications • Integration of a wide variety of sensor data and operational information into asset health monitoring tools and capabilities