Quadrennial Technology Review 2015

Chapter 3: Enabling Modernization of the Electric Power System

Technology Assessments

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Transmission and Distribution Components

U.S. DEPARTMENT OF ENERGY

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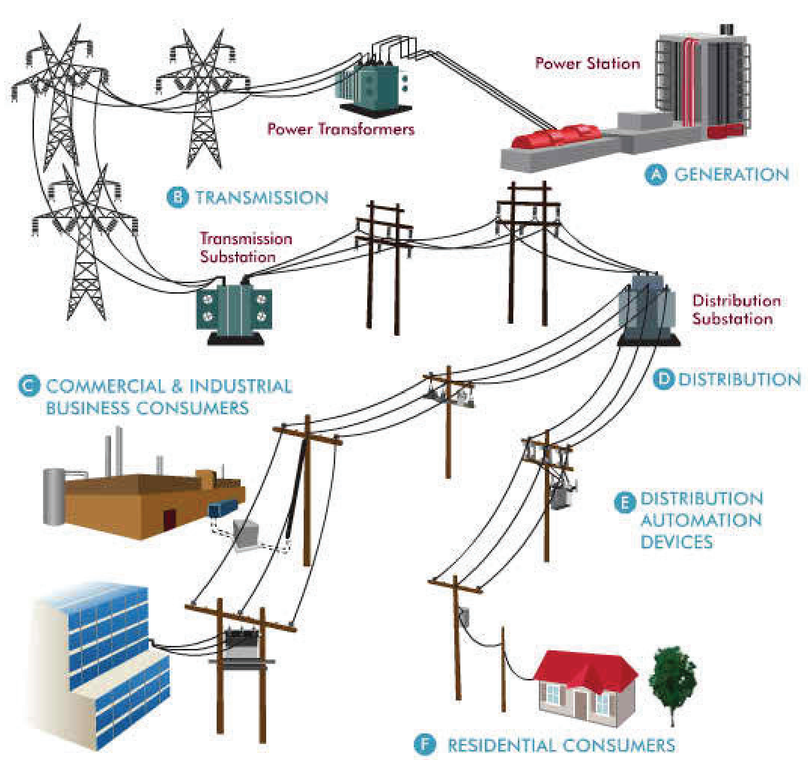
Transmission and Distribution Components

Chapter 3: Technology Assessments

Introduction

Today's electric power system was designed for efficiency, reliability, ease of operation, and to meet consumer needs at minimum cost. The grid of the future must maintain these characteristics while meeting a number of new requirements: supporting the integration of various clean and distributed energy technologies, meeting the higher power-quality demands of modern digital devices, and enabling consumer participation in electricity markets. Increasing the projected penetration levels of variable renewable resources, distributed generation, community energy storage, electric vehicles, and the number of active customers will require substantial changes to how the grid and its various components are designed, controlled, and protected.

Figure 3.F.1 Electricity Delivery Network

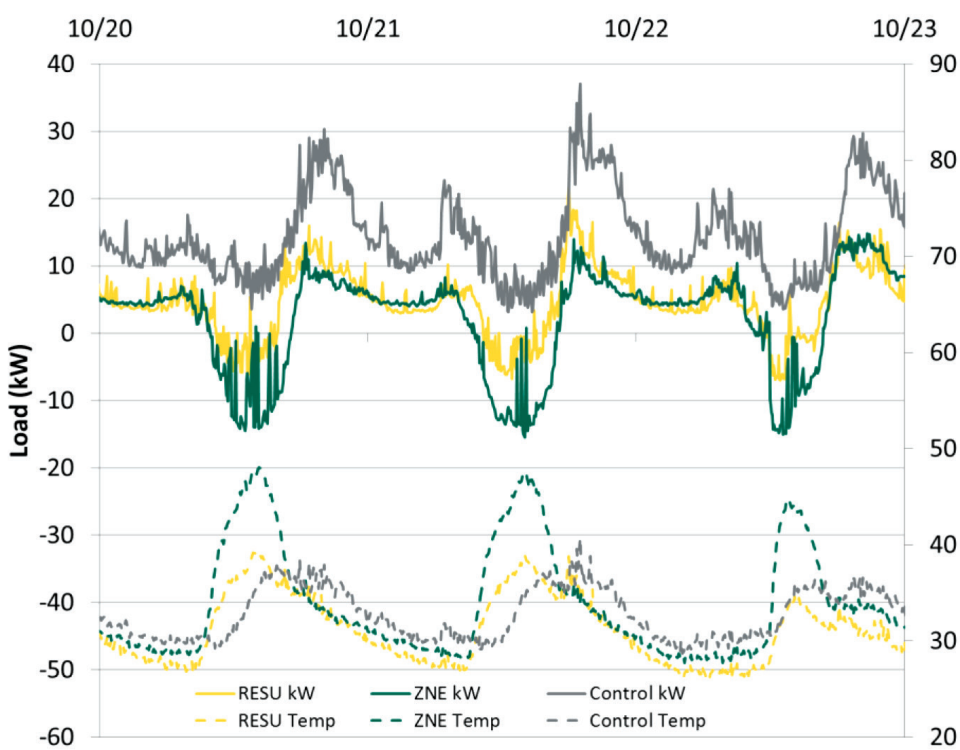


Approximately four trillion kWh of electric energy are consumed annually in the United States.[1] This electric energy is delivered from generators to consumers through an intricate network of transmission lines, substations, distribution lines, and transformers, as illustrated in Figure 3.F. 1. The transmission and distribution (T&D) components that make up this network are generally exposed to the elements and are vulnerable to natural and man-made threats. To ensure a reliable and resilient electric power system, grid components should be designed and built to withstand the reasonable impacts of lightning strikes, extreme weather events, electrical disturbances, accidents, equipment failures, cyber and physical attacks, and other stressors. The impacts of climate change could be substantial and worsen over time, especially flooding events, which can have a significant impact on reliability.[2] The changing landscape of generation and load-side technologies is fundamentally altering electric power flows and the physical phenomena for which future grid components will need to be designed. In addition, federal policies related to carbon emissions reductions will impact the bulk generation mix in future years, necessitating the upgrade and building of transmission equipment.

The more dynamic operating environment associated with increased penetration of variable renewable resources and distributed energy resources (DERs) present a unique challenge for current grid components. For example, transformer load tap changers typically operate several times per day (either in an automated or remotely controlled manner) to help maintain voltage limits and power quality along a distribution feeder. High penetration of rooftop photovoltaic (PV) can lead to voltage and frequency violations due to the variability of PV power generation. This in turn will require more frequent operational adjustments to maintain voltage and frequency within acceptable limits. These changing system conditions can reduce component useful lifetimes and increase costs, with accelerated maintenance and replacement schedules. Distributed energy resources also introduce new challenges, with reversed power flows, increased harmonics, and potentially larger fault currents on distribution systems. For example, reverse power flow can result in excessive heating of distribution transformers,[3] as shown in Figure 3.F. 2, and potentially reduce the life span of the asset. Understanding and mitigating the impact of these issues on grid components, old and new, are essential to ensure the future grid can continue to deliver electricity in a safe, stable, and reliable manner.

Figure 3.F.2 Excessive Transformer Heating

Credit: Southern California Edison Company



Key: **RESU** = residential energy storage unit; customers have storage available, thereby dampening the magnitude of feedback to the grid, resulting in less-severe temperature increases; **ZNE** = residential zero-net-energy customer; customers have the opportunity for more frequent feedback to the grid, resulting in higher temperatures.; **Control** = residential control group customer.

In addition to the rapidly changing landscape of power flows and physical phenomena that grid components need to accommodate, the age of some grid components is increasing the urgency for solutions.[4] Currently, 70% of power transformers are 25 years or older, 60% of circuit breakers are 30 years or older, and 70% of transmission lines are 25 years or older.[5] The age of these components degrades their ability to withstand physical stresses and can result in higher failure rates. Failure of key grid components can lead to widespread outages and long recovery times. This situation represents a high loss of revenue for utility companies and for customers who require power to do business and provide services. Consequently, appropriate maintenance of power system equipment is of significant importance. For instance, a single power transformer that is damaged can temporarily disrupt power to the equivalent of 500,000 homes, and it can take up to two years to manufacture a replacement.[6] Moreover, power outages from weather-related events and other causes are estimated to cost the United States $28–$169 billion annually.[7]

In 2011, the American Society of Civil Engineers (ASCE) estimated an average expenditure of $27.5 billion annually for electric transmission and distribution investments in the United States, and they predict a cumulative investment shortfall of $331 billion by 2040.[8] The average annual expenditures estimated by ASCE are consistent with data reported by the Edison Electric Institute in 2012.[9] Based on these estimates, approximately $1.1 trillion will be needed to replace, expand, and upgrade the U.S. electric grid through 2040. The total amount needed includes the net investment (investments in addition to those made for reliability or replacement purposes) of $338–$476 billion over a 20-year period, estimated by the Electric Power Research Institute to realize the full value of the "smart grid."[10] Consideration of policies related to carbon emissions and climate change have an inherent impact on this estimate.

The investment cycle needed to replace, upgrade, and expand the U.S. transmission and distribution systems has already begun, with annual spending increasing from $28 billion in 2010 to $44 billion in 2013.[11] The procurement of transmission and distribution goods and services today centers on refurbishment and upgrades of existing facilities and field assets, increasing the intelligence of older passive analog equipment to gain visibility to grid conditions.[12] Table 3.F.1 provides an estimate of the approximate magnitude of various

Table 3.F.1 U.S Transmission and Distribution Market Segments[13, 14, 15, 16, 17]

U.S. Transmission and Distribution Market Segments (2013)	Estimated Market Size ($ Billions)
Transformers (power and distribution)	5.0–6.0
Cables and Conductors	8.0–9.0
Towers, Insulators, and Fittings	2.0–2.5
Switchgear (e.g., breakers, "sectionalizers," "reclosers," fuses)	4.0–4.5
Meters (advanced metering infrastructure, phasor measurement unit, etc.)	2.0–2.5
Substations (turnkey solutions)	4.5–5.0
Power Systems (e.g., high voltage direct current, flexible alternating current transmission system, integrated solutions)	5.5–6.0
Utility Automation (e.g., asset monitoring, instrumentation, control)	2.5–3.0
Operational Platforms, Systems, and Services	2.5–3.0
Construction (substation, lines, towers)	3.5–5.0
Total	**39.5–46.5**

grid market segments in 2013. Missing the window of opportunity to develop and install next-generation transmission and distribution components required for a future grid can slow its transformation and impose significant opportunity costs to society.

The "smart grid" revolution has primarily focused on applying advances in digital information and communication technologies to the power system to improve operational performance in a changing system with increased variability and uncertainty. However, the full value of grid modernization can only be achieved through commensurate advances in T&D components and changes on a system level to enable the grid to be flexible and integrated. Next-generation technologies—based on innovations in material science, such as nano-composites, wide band-gap semiconductors, advanced magnetics, new insulators and dielectrics, and high-temperature superconductors—can unleash new capabilities for the grid and improve the performance and lifetimes of current designs. New component technology requirements will need to balance improved functionalities that support greater consumer self-generation, improve resilience, and increase flexibility while managing total costs.

Transformers

Transformers are one of the fundamental building blocks of today's electric grid; essentially all 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 voltages vary within these categories (see Table 3.F.2). Power transformers are typically located at generator plants and substations, while distribution transformers are typically located in industrial, residential, and commercial areas, directly supplying power to the end user in low or medium voltage service (Figure 3.F.3).

Table 3.F.2 Overview of General Transformer Groups[18, 19]

Type	Class	Voltage Ratings (kV)
Power Transformers	Extra High Voltage	345–765 kV
	High Voltage	115–230 kV
	Medium Voltage	34.5–115 kV
Distribution Transformers	Distribution Voltage	2.5–35 kV

Figure 3.F.3 Examples of Power Transformers (left) and Distribution Transformers (right)[20]

Power Transformers

Power transformers cost millions of dollars, weigh 100 to 400 tons, are usually made to order, and can take up to 20 months to replace, depending on material availability. The lack of domestic manufacturing for these transformers, in particular 500 kV and 765 kV, contribute to long lead times and can present an energy security challenge. In 2010, only 15% of U.S. demand for large power transformers (LPTs) was met from domestic production. However, this situation has been improving, with several new and enhanced facilities opening recently. In recent years, as many as four transformer manufacturing units have come online in the United States alone.[21] This is expected to ramp up the domestic manufacturing capability of transformers.

Because power transformers operate continuously and are generally highly loaded, they must be designed to be exceedingly reliable and efficient. At present, the highest efficiencies for power transformers are around 99.85%.[22] While there are no moving parts in most transformers, the insulation around the conductors weakens as a result of chemical changes brought about by thermal aging. Of the several hundred LPT failures between 1991 and 2010 that were tracked in the United States, most were due to failures in insulation, 28% were due to electrical disturbances (switching surges, voltage spikes, line faults, etc.), 13% were due to lightning strikes, and 9% were from insulation failure at normal voltages.[23] Additional research on new materials for insulation, conductors, and cooling of transformers would help increase their reliability.

Applied research in low-loss magnetic core materials and electrical conductors for windings can improve transformer efficiencies. Joule heating in transformers typically accounts for losses in the range of 1%–2%, depending on the type and ratings of the transformer.[24] Efficiency and total cost of ownership are the main factors that drive improvements in transformer development. Advanced insulators and higher quality dielectric materials, such as gases, can be utilized in transformer design to allow operations at higher temperatures and voltages, increasing the lifetime and reliability of transformers. Superconducting transformers have the potential to achieve higher levels of efficiency. By taking advantage of the high temperature superconducting (HTS) material's unique ability to conduct electricity with no resistance when cooled below a certain temperature, a transformer can be designed lighter, more compact, and with much reduced energy losses. In this transformer, both the coolant and the insulating fluid would use liquid nitrogen—a nonflammable, nonhazardous substance.[25] Embedded sensors for real-time diagnostics and device monitoring can also improve performance and support preventative, just-in-time maintenance.

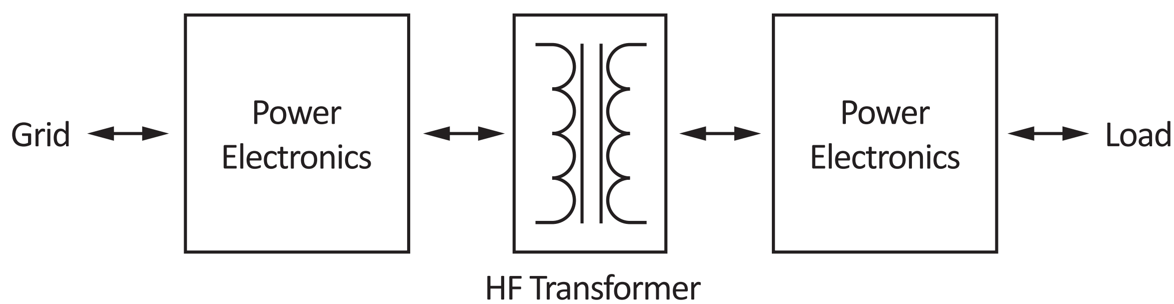
Modeling and simulation can be applied to optimize current designs and explore new concepts that can facilitate system recovery in the event of a failure. Modularized design components, standardization, and recovery concepts can help improve resiliency. The requirement of shorter pay-back time for these future transformers will influence technical decisions beginning with the design, choice of materials, and maintenance strategies. Designing for shorter lifetime and less maintenance may require additional and improved monitoring and diagnostic tools.[26] The U.S. Department of Energy (DOE) and the U.S. Department of Homeland Security (DHS), along with several industry partners, worked to develop the Recovery Transformer (RecX). The RecX prototype is lighter, smaller, easier to transport, and quicker to install than a traditional LPT. In the future, application of solid-state power electronic devices to power transformers may also provide some new capabilities, such as active controls and improved recovery concepts. Novel approaches to power conversion, such as high frequency resonant power conversion, can leverage higher switching frequencies and also eliminate the need for large and expensive fault protection equipment required of standard 60 Hz power transformers. To the extent possible, security enhancements should also be embedded into the physical design of LPTs. Resistance to geomagnetically induced currents, electromagnetic pulses, and physical attacks should be incorporated into transformer designs.

Distribution Transformers

Distribution transformers are ubiquitous and cost $1,000–$55,000, depending on their rating. While power transformers are designed and optimized to function at high load continuously, distribution transformers operate at low loading for most of the day. This daily variation makes design parameters wider, optimizing for 10%–60% of peak loading, and results in lower efficiencies compared to power transformers.[27] Recently, new standards have been released by DOE that will increase the minimum efficiency of these transformers.[28] Advanced materials can be leveraged to achieve efficiencies in a cost-effective manner. However, as more DERs are deployed, the variability of loading on these transformers will increase, along with more dynamic voltage fluctuations and current flows. It will be important to understand how these changes will impact the efficiency, lifetime, performance, design, and protection of these critical grid components in the future. The research emphasis for future distribution transformers includes adding capabilities for voltage regulation, monitoring, reactive power support, and communications.

In addition to the material advances that can be applied to both power and distribution transformers alike, there may be a unique opportunity for solid state transformers (SSTs) in future transmission and distribution systems. An SST is a design concept that combines power electronic devices and high-frequency magnetics (see Figure 3.F.4) that can lead to more compact transformers and provide new control capabilities.[29] The global market for SSTs is expected to reach about $5 billion at a compound annual growth rate of 82.3% by 2020, according to a 2013 report.[30] A move toward a widespread integration of SSTs into the power system will require a major increase of manufacturing capacity for these components. The establishment of a supply chain and subsequent creation of economies of scale can bring prices for SSTs down considerably.

Figure 3.F.4 Conceptual Diagram for Solid State Distribution Transformer Function



A solid state distribution transformer (SSDT) will not be a drop-in replacement for a distribution transformer but will be utilized in strategic locations for their enhanced functionality and flexibility. For instance, an SSDT can be used to mesh radial segments of the distribution network, perform voltage regulation, and supply reactive power as well as be used to form hybrid AC and DC systems. 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.

Current SSDT designs are based on silicon insulated gate bipolar transistors (IGBTs) and face challenges associated with cost, reliability, and efficiency. Leveraging advances in wide band gap semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), can enable new designs and configurations that could be more cost-effective.[31, 32] However, significant advances in power electronic devices using these new materials are needed to achieve the high-power, high-frequency, and high-reliability requirements of an SSDT design. Trade-offs between system performance, device voltage ratings, and price must be weighed in future designs, configurations, and applications. Focused research and development (R&D) are needed to develop new solid state materials and components to meet these unique requirements.

The National Science Foundation has sponsored the design and development of next generation SSDTs.[33] Researchers at the Future Renewable Electric Energy Delivery and Management Systems Center developed a fast, small, super-efficient power transformer that greatly exceeds the performance of earlier designs, with models showing 90% efficiency.[34, 35] However, SSDTs still face many challenges associated with costs, reliability, and system efficiency. Additionally, an SSDT can provide services to the distribution network for which current markets do not attribute a specific monetary value. This presents a difficulty in valuing the benefit of an SSDT and setting a price for competitive market entry.

Distribution transformers with intelligent sensors, communications, and controls would also allow users to monitor usage in real time, enhancing the stability and controllability of the power distribution grid. By augmenting existing distribution transformer designs with semiconductor devices, these technologies can provide new and enhanced capabilities to the future grid as well. Dynamic control of real and reactive power can optimize the efficiency of distribution systems, improve power quality in a more dynamic operating environment, and limit fault currents.

Cables and Conductors

Cables and conductors are the primary carriers of electricity and are critical components for the reliable, efficient, and cost-effective delivery of power. Conductors are suspended overhead from towers and poles and are generally not insulated except at lower voltage levels. In contrast, cables are always insulated and are generally used in underground applications, such as for 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. Occupying less space, reducing exposure to electromagnetic frequency, not contributing to visual pollution, and lower life-cycle costs are metrics that can be used to measure improvements in cables and conductors.[36]

Underground cables are generally more expensive, per mile, than overhead conductors but may make economic sense when other factors are taken into account. There is no precise cost for building cables and conductors because each construction project is unique. Depending on load, number of customers, various construction parameters, and the choice of technology (AC versus DC), cost per mile can vary significantly as illustrated in Table 3.F.3. These costs are high-level estimates based on averages of a utility's typical construction approach and include various variables, including customer density (urban, suburban, and rural), soil conditions (sandy to rocky), labor costs, construction techniques, vegetation management, equipment, and voltage levels.

As electric power demand increases and shifts due to economic growth, demographic changes, and the use of new technologies, more cables and conductors will be needed to increase the capacity and the interconnectivity of the grid to meet this flux in demand. While distributed generation may be used to offset some of this demand growth, the most flexible and globally optimal solution tends to be one that enables access to a wide diversity of energy resources. Historically, installation of new cables and conductors has been the preferred solution to increase transmission capacity but with limited right-of-way and opposition from local communities; "reconductoring"[38] has emerged as a practical solution.

Development of advanced cables and conductors that have lower losses or that have higher current- carrying capabilities can support more cost-effective reconductoring as well as new installations. Advanced cables and conductors are expected to reduce transmission and distribution losses and increase energy supply to end users. HTS cables can deliver up to five times more electricity than traditional conventional copper or aluminum cables and have the potential to address the challenge of providing sufficient electricity to densely populated areas.[39]

Table 3.F.3 Cost per Mile for New Transmission and Distribution Construction[37]

Cost per Mile: New Construction Transmission						
	Overhead			Underground		
	Urban	Suburban	Rural	Urban	Suburban	Rural
Minimum	$377,000	$232,000	$174,000	$3,500,000	$2,300,000	$1,400,000
Maximum	$11,000,000	$4,500,000	$6,500,000	$30,000,000	$30,000,000	$27,000,000

Cost per Mile: New Construction Distribution						
	Overhead			Underground		
	Urban	Suburban	Rural	Urban	Suburban	Rural
Minimum	$126,900	$110,800	$86,700	$1,141,300	$528,000	$297,200
Maximum	$1,000,000	$908,000	$903,000	$4,500,000	$2,300,000	$1,840,000

The Energy Information Administration estimates that national electricity transmission and distribution losses average about 6% of the total electricity generated in the United States each year.[40] These technologies can be improved by leveraging material advances and new designs. These enhancements will also need to consider manufacturability to manage costs.

Overhead Conductors

The operating temperature of conventional conductors should not exceed 100°C; temperatures in excess of this may cause significant damage to the aluminum portion of the conductor. This thermal limit constrains the amount of power that can flow through an overhead line at a given voltage. Conductors that are rated at higher temperatures can carry larger currents and deliver more power. However, higher temperatures will result in more thermal expansion and greater sag between towers and poles. Excessive sagging can result in safety hazards and increase the risk of power failures if the line comes into close proximity or contact with other objects. In the last 20 years, a class of conductors referred to as high temperature low sag (HTLS) has come into use for transmission of larger quantities of power by using existing right-of-ways. HTLS conductors are made of stronger mechanical cores (e.g., steel or composite) that reduce line sag during operation at increased temperatures, as shown in Table 3.F.4.

Table 3.F.4 Examples of HTLS Conductors and Their Temperature Resistance[43]

HTLS Conductor	Rated Temperature
Aluminum Conductor Steel Supported	200°C
Zirconium Alloy Aluminum Conductor Invar Steel Reinforced	150°C–210°C
Gap-Type Heat Resistant Aluminum Alloy Conductor Steel Reinforced	150°C
Aluminum Conductor Composite Reinforced	210°C
Composite Reinforced Aluminum Conductor	150°C
Aluminum Conductor Composite Carbon Fiber Reinforced	210°C

Material innovations can be applied to the development of next-generation HTLS conductors with higher thermal rating, strength, and lower resistance compared to conventional conductors. For instance, Ames Laboratory is developing an aluminum (Al) matrix composite reinforced with calcium (Ca) metal nano-filaments. Aluminum and calcium are both lightweight materials and highly conductive, and the resulting Al/Ca composite wires have shown enhancements, such as lower density than Al alone and good corrosion resistance.[41] Results of first generation Al/Ca wires showed degradation at about 285˚C, which sets a (conservative) rated operating temperature of 250˚C. Table 3.F.5 shows some of the characteristics for Al/Ca composite wires that are superior to conventional conductors. Other new materials such as ultra-conductive copper are projected to produce a 50% reduction in resistivity while simultaneously increasing strength and thermal conductivity.[42]

Table 3.F.5 Comparison of Aluminum Composite Steel Reinforced (ACSR) versus Al/Ca Composite Conductor[77]

Conductor Characteristic	ACSR (30/7)*	Al/20 vol. %Ca Composite (37 strand cable)
DC Resistance@20˚C (ohms/1000 ft.)	0.0279	0.0236
Breaking Strength (lbs.)	28,900	56,100**
Weight/1000 ft. (lbs.)	946	627

* Southwire Wood Duck conductor; 30 Al strands: 1350-H19; 7 steel strands: Class A galvanized
** Calculated value.

As the electrical resistance of a material increases with temperature, line losses increase with elevated conductor temperatures. One promising approach to improve performance of overhead conductors is to employ high emissivity coatings. The use of coatings with an emissivity greater than 0.8 appears to produce a 20% reduction in the operating temperature of conductors compared to the control. Other innovative materials to consider for the next generation of overhead conductors are those that have dual use for HVAC and high voltage direct current (HVDC) applications. Innovative coatings that reduce corrosion, minimize icing, and increase heat dissipation can also extend the lifetime of overhead conductors.

Underground Cables

Underground cables are more complicated and expensive than overhead conductors due to the need for insulation, shielding, thermal management, and extra considerations. Owing to the significant reactive power losses associated with alternating current (AC) in underground and underwater applications over long distances, HVDC technologies tend to be the more economical solution. Another option is the use of superconducting cables, which have essentially no electrical resistance. However, the use of this technology is very limited due to the high cost of ownership, stemming from the refrigeration system and additional maintenance.

DOE's Office of Electricity Delivery and Energy Reliability (OE) supported an HTS program from 1987 through 2010, showcasing the use of HTS-based applications in enhancing the per¬formance of electricity transmission and distribution systems.[44] Superconducting DC cable systems are inherently suitable for long-distance, high-power, bulk energy transfer without the disadvantages of either high-voltage DC or extra high-voltage AC systems. The superconducting DC cable is projected to have greater reliability and security, substantially lower losses, a smaller right-of-way footprint, fewer siting restrictions, and the ability to be terminated at distribution voltages in or near load centers.[45] The program developed HTS materials and devices for a wide variety of applications with an emphasis on underground cables, moving HTS from basic research to large-scale demonstration projects.

Three projects under this program, hosted by electric utility companies in Albany, New York, Columbus, Ohio, and Long Island, New York, resulted in significant technological achievements. The Long Island cable was the world's first transmission voltage superconducting cable; the Albany cable was the world's first cable to use second generation wire; and the Columbus cable operated for approximately six years serving real world customers.[46] In 2014, DHS announced that it is leading the planning phase for a resilient electric grid cable project in Chicago based on HTS technology. This technology aims to increase the resiliency, robustness, and reliability of the Commonwealth Edison's electric grid.

Activity in HTS cable technology is growing worldwide, particularly in Japan, Korea, Russia, and Europe, with a variety of grid demonstration projects underway.[47] For instance, a superconducting power line cable in the city of Essen, Germany (the AmpaCity Project), is expected to carry five times as much power as a conventional cable and result in substantial cost savings.[48] Opportunities to increase the viability of HTS cables include improving performance and reducing the cost of the superconducting wire. Reducing the cost of the refrigeration system and new materials with higher transition temperatures are other opportunities.

Development and demonstration of HVDC cables at higher voltages is another research area. In 2011, cross-linked polyethylene cables for HVDC had a rating of ±350 kV[49] but are now approaching ±500 kV. DOE's Advanced Research Projects Agency-Energy (ARPA-E) Green Electricity Network Integration (GENI) program supported improvements in this technology, such as the use of nano-clay for next-generation HVDC cables. A research emphasis is also needed on superconducting HVDC cables, fluid-filled polypropylene paper laminate cables, and underground power delivery solutions. Finally, research on embedded sensors, new insulation materials, thermal management systems, and installation and maintenance techniques can improve the performance and lower the costs of using underground cables.

Connectors

Closely associated with cables and conductors are connectors that provide the necessary mechanical and electrical couplings between adjacent power line segments. Compression connectors for overhead lines are made by crimping a soft aluminum sleeve onto the two ends of conductors to be joined. These connectors are basically the weak links in the electricity delivery network, where power transmission can be limited by the connector resistance and disruptions can occur owing to mechanical failures. As electrical loads on existing transmission lines have increased, the performance and integrity of aging connectors continue to degrade owing to accelerated surface oxidation from environmental exposure and elevated operating temperatures.[50] Research opportunities include applied materials research to limit the surface oxidation rate and advanced designs for enhanced mechanical and electrical connectivity. In addition, innovative low-cost sensing and monitoring techniques that can accurately provide information on the structural health of these connectors will move their maintenance from time-based to condition-based scheduling. Research emphasis is needed on developing standards for the connecters used to dead-end and splice overhead conductors that operate above 93°C.

Power Flow Controllers

Electric power on the grid 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 a networked system is limited by the weakest line, despite the existence of parallel paths. As a result, the 642,000 miles of transmission lines in the United States are only loaded well below 50% of their capacity, on average, indicating suboptimal asset utilization.[51] However, some of this excess capacity is needed to ensure reliable operations in the event of a contingency and is considered in operations planning and generator dispatch. During periods of high demand, bottlenecks will develop on the transmission system that can prevent access to lower-cost energy resources, such as wind and solar. These congestion costs can be quite significant, with PJM reporting $1–$2 billion in congestion costs annually over the last decade.[52] These extra costs are generally recovered through more expensive electricity to customers. Congestion is extremely volatile and transient, which creates the need for power flow controller systems that are flexible and capable of being moved to new locations as congestion moves and market dictates.

Enhanced power flow capabilities within the transmission and distribution system will fundamentally change how the grid can be controlled and managed. Greater deployment of power flow controllers can directly alleviate line congestion, increase asset utilization, and optimize generator dispatch for cost savings. Additionally, the enhanced grid flexibility can support increased penetration of variable renewable resources and improve system resiliency. For example, if an area is experiencing an outage due to damaged components, power flow controllers can route power around those affected areas and continue to provide electricity to critical loads.

Two categories of power electronic systems that can provide enhanced flow control are HVDC converters and flexible alternating current transmission system (FACTS) devices. Criteria and metrics used for measuring improvements in converter technologies could include increasing capacity, enhancing reliability, improving controllability, preserving the environment, and increasing power density and power efficiency.

HVDC converters decouple power flows from the synchronous nature of the grid, whereas FACTS devices work within the synchronous nature of the grid and alter line impedances to control power flows. In addition to developing the components, there is also a need to develop new control theories that can utilize these power flow control capabilities and integrate them into next-generation grid management systems. Potential new applications include using power flow controllers to damp oscillations and provide artificial inertia to increase system stability.

Within DOE's portfolio, there are multiple program areas and projects that involve power electronics that can be leveraged for the development of power flow control capabilities. One of the largest funding organizations for high-power electronics is the Defense Advanced Research Projects Agency. The research and application of power electronic devices into power flow controllers will require advancements in several areas, including reducing cost of semiconductor devices, developing advanced control systems, reducing harmonics and electromagnetic interference, and improving reliability of active and passive components.[53]

HVDC Converters

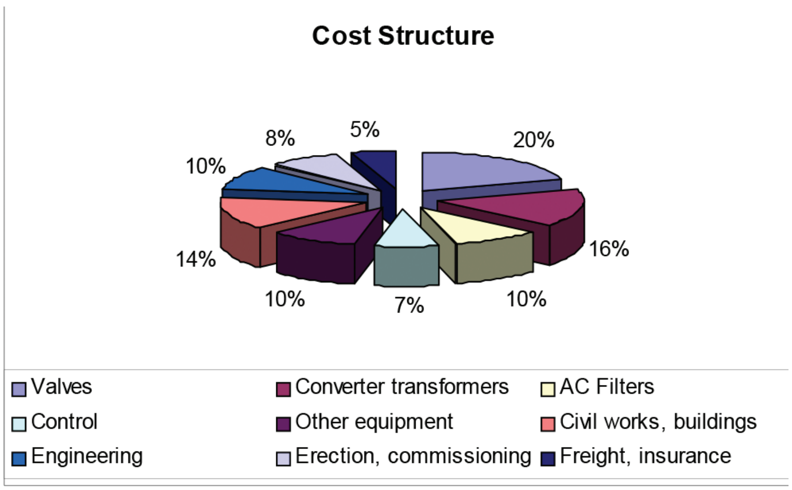
HVDC converter technology is considered to be a mature technology and has been mainly deployed for point-to-point delivery of large quantities of power (e.g., greater than 500 MW) over long distance (e.g., greater than 300 miles). Modern HVDC systems can transmit up to three times more power (megawatts) as conventional AC systems at the same voltage and are the technology of choice for bulk transmission over long distances.[54,55] The proposed Plain and Eastern Clean Line Transmission Project is an example of a major HVDC installation that will have the capacity to deliver 3,500 MW primarily from renewable energy generation facilities to load-serving entities in the mid-south and southeastern United States.[56]

Moreover, given the increasing difficulties in obtaining permission for siting new power lines in both urban and rural areas, underground cables are often the solution for increasing capacity. Due to reactive power losses in high-voltage AC configurations (overhead as well as underground), HVDC systems tend to be more economic, despite higher losses in the converter substation compared to a standard AC substation. Other applications of HVDC converter technologies include back-to-back connections to share power between two asynchronous systems, improving reliability and stability, and the creation of HVDC networks for improved system efficiencies, such as with off-shore wind farms. An HVDC network may also provide opportunities to reduce reserves, improve load diversity (interregional transport of capacity), reduce variability of renewable resources, and transport energy to meet renewable portfolio standards.[57]

There are currently two commercial HVDC converter technologies: line commutated converters (LCCs) based on thyristors and voltage source converters (VSCs) using IGBTs. LCCs are more established and have losses of about 0.7% per station,[58] while VSCs are newer and have losses of about 1.4%–1.6% per station. While losses are higher for VSCs, IGBTs enable simpler configurations that reduce total system costs. VSCs require little to no filtering and no reactive power compensation and are more compact, which reduces or eliminates associated costs as compared to LCCs (see Figure 3.F. 5). Additionally, VSCs have inherent black start capabilities, enable multiterminal configurations, and are easier to deploy without complex studies and system reinforcements. Presently, all of the HVDC installations within the United States are thyristor based. HVDC deployment in the United States has been limited to 31 transmission facilities, with 44 across the North American grid.[59]

Figure 3.F.5 Approximate Cost Structure of an LCC HVDC Converter Station[60]

Credit: D.M. Larruskain, I. Zamora, A.J. Mazn, O. Abarrategui, and J. Monasterio, "Transmission and distribution networks: AC versus DC," in Proc. 9th Spanish-Portuguese Congress on Electrical Engineering, 2005.



While VSCs hold a lot of potential, there are still many technical challenges. LCCs are still used for large power transfer because current VSC systems are limited to ±500 kV. Additionally, HVDC networks are limited in application owing to the cost of tapping into a line. With advances in VSC technology, higher power ratings and cost-effective multiterminal converters can be realized, but complex fault isolation and protection schemes will still be needed. Multiterminal HVDC (MTDC) networks have seen application in offshore wind collector systems but have the potential to enhance system reliability for onshore applications as well. Controls for the coordination of MTDC terminals must be perfected before commercial systems are widely deployed.

The difficulty in siting new overhead transmission lines may present a new value proposition for HVDC technologies. There may also be applications for medium voltage direct current (MVDC) systems, such as improving resilience by connecting substations or increasing efficiency by utilizing DC distribution buses. Strategic placement of MVDC converters can also support the devolution and reconstitution of nested or networked microgrids. Research in modular multilevel converters (MMCs) can enable higher voltage and higher power applications, using market-available semiconductor devices. MMCs reduce stress on switching components, thereby enhancing reliability. Additionally, inherent fault tolerance of high frequency resonant converter designs is also desired.

Broad deployment of these technologies will require reliability and cost-effectiveness. Accordingly, cost-benefit analysis of power flow controllers is a key research area to understand the appropriate cost levels to target. Other research opportunities include new system designs and enhancements enabled through the use of wide band gap semiconductor devices based on SiC and GaN. The use of these materials allows for higher temperature and higher frequency operations, which translates to smaller passive component and thermal management systems that can reduce overall system costs. These systems will also require passive materials that are capable of performing well under conditions of elevated temperature and high frequency. Additionally, developing new device architectures (e.g., lateral devices) can fundamentally change the design paradigm for HVDC and MVDC converter technologies because thyristors and IGBTs are both vertical devices.

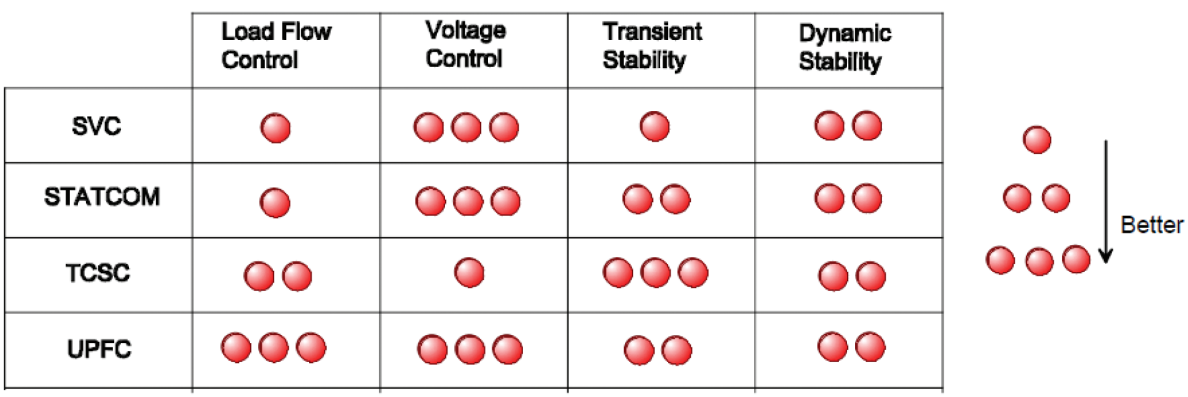
FACTS Devices

In theory, AC transmission and distribution systems should be able to carry power up to the thermal design limit. However, the power flow is usually constrained to a lower limit owing to reactive power considerations and reliability requirements determined through contingency analysis to ensure security of the grid under varying system conditions. Improved power flow control of AC systems can be achieved through the use of various technologies that can be generally categorized as mechanical-based and power electronics-based technologies. Tap-changing or phase-shifting transformers, switched shunt capacitors and inductors, and voltage regulators are mechanical-based technologies that provide a coarse level of control. FACTS devices are power electronics-based technologies and represent a wide range of controllers with different designs and different levels of power flow control capabilities, as summarized in Figure 3.F.6. Reactive power support from FACTS devices can help to increase power transfer capabilities, improve voltage stability, and enhance system stability. As more variable renewable resources are deployed, these dynamic control capabilities will become more important.[61] Criteria and metrics used for measuring improvements in FACTS devices could include their ability to meet voltage stability criteria (e.g., voltage or power criteria with minimum margins), dynamic voltage criteria (e.g., minimum transient voltage dip/sag criteria [magnitude and duration]), transient stability criteria, and power system oscillation damping.

Figure 3.F.6 Summary of FACTS Devices and Capabilities[62]

Credit: Black & Veatch Corporation

Facts Device	Increased Power Transfer	Improved Voltage Stability	Enhanced Rotor Angle/System Frequesncy Stability
SVC	Indirect	Direct	Inderect
STATCOM	Indirect	Direct	Indirect
TCSC/SSSC	Direct	Indirect	Direct
UPFC/IPFC	Direct	Direct	Direct

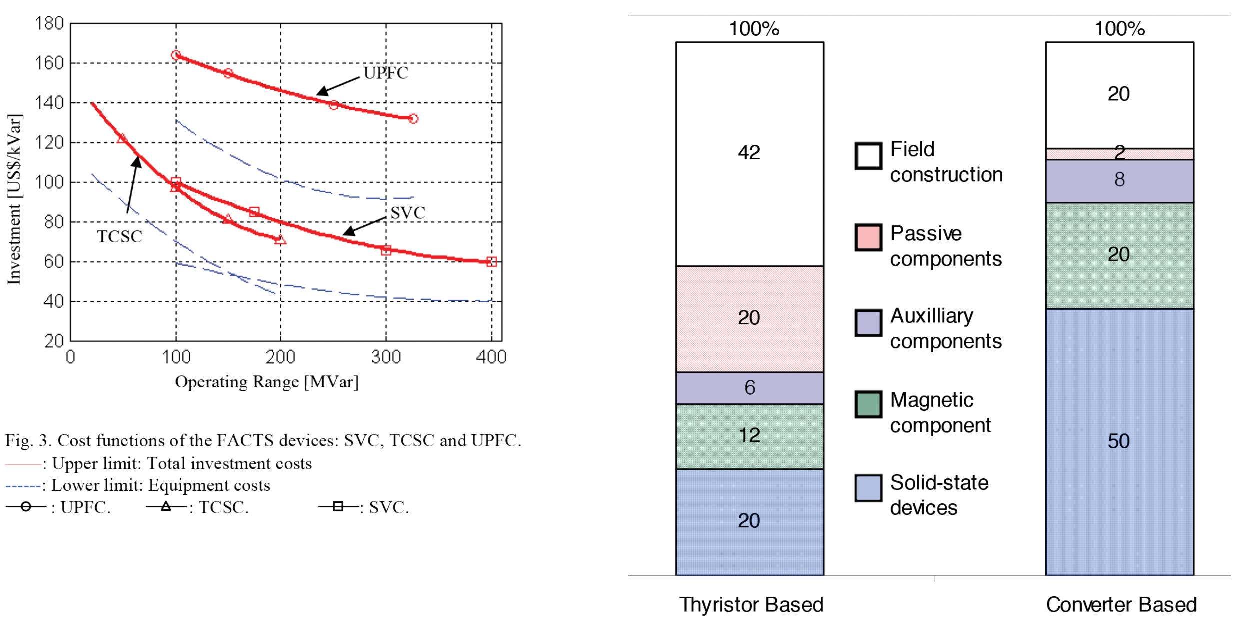


Key: **SVC** = static VAR compensator; **STATCOM** = static synchronous compensator; **TCSC** = thryistor controlled series compensator; **UPFC** = unified power flow controller; **IPFC** = interline power flow controller; **SSSC** = static synchronous series compensator.

FACTS devices, especially “high-end” products, such as unified power flow controllers (UPFCs) and interline power flow controllers, can address even the most challenging power flow control problems. While FACTS are deployed on transmission systems to improve load flow, they are also used to mitigate problems on distribution systems. However, the deployment and application of these technologies have been limited by very high total systems costs. Figure 3.F.7 shows the cost curves for various FACTS devices and a comparison of the cost breakdown for thyristor-based FACTS (static VAR compensators and thyristor-controlled series compensators) and converter-based (IGBT-based) FACTS (STATCOMs and UPFCs). If significant improvements can be made in the cost and performance of power electronic devices (solid state devices), there can be substantial impact on cost reductions for the high-end FACTS devices. As with HVDC converter technologies, the use of wide band gap semiconductor devices and new device topologies can change design paradigms and result in lower overall system costs. Current FACTS devices are about 5 to 10 times more expensive than electromechanical-based reactive power compensation methods, and future improvements will need to compete with these technologies. A move toward broader integration of FACTS into the system will require a major increase of manufacturing capacity for these components. The establishment of a supply chain and subsequent creation of economies of scale can bring prices for FACTS down considerably. Further research geared toward new system designs and advanced power electronic devices can help to bring costs down to $10–$40/kVAR, making the technology competitive with other methods of power flow and voltage control.

Figure 3.F.7 Summary of FACTS Devices and Capabilities[62]

Credit: Figure Left: L.J. Cai and I. Erlich, “Optimal Choice and Allocation of FACTS Devices using Genetic Algorithms,” in Power Systems Conference and Exposition, IEEE-PES, 2004; Figure Right: Oak Ridge National Laboratory.



In addition to achieving cost reductions through improvement in lumped high-rating (10-300 MVAR) devices, the concept of distributed FACTS (DFACTS) has emerged in the past decade. DFACTS comprise a number of low-rating (0.01–2 MVAR) devices distributed along power transmission lines. Devices along a single line or coordinated across multiple lines can provide control capabilities in aggregate. This distributed concept has many advantages, including lower cost, lighter weight, easier installation, and the ability to be mass produced. DFACTS have been supported by ARPA-E’s GENI program, but more work is needed to lower costs, increase capabilities, and develop and demonstrate control schemes.

Another concept that can be utilized for power flow control is the magnetic amplifier. By leveraging power electronics and a magnetic core, low voltage signals can be amplified to control power flows on high voltage transmission lines. Construction of the magnetic amplifier power flow controller is somewhat similar to that of a power transformer, and utilities could be more comfortable with its installation. Many technical challenges still remain, such as high voltage insulation, shielding, and demonstration, but these systems are estimated to cost less than $10/kVA.

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Protection Equipment

As power flows and system dynamics change from the deployment and use of advanced technologies, the role and configuration of protective equipment (such as circuit breakers, surge arresters, and fault current limiters) will also need to evolve. Moreover, as protection schemes become more complex due to two-way power flow that is inherent within a modern power system, flexible protection schemes will be required to adapt to changing conditions on the grid. Additionally, 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 damage or destroy expensive grid component technologies—new and old—such as power transformers, HVDC converters, FACTS devices, and even circuit breakers.

Circuit Breakers

Circuit breakers are mechanical switches and protection devices that electrically isolate circuits and components under normal operating conditions or automatically in emergency situations such as sustained faults. The command to isolate the circuit is usually provided by protective relays. Although electromechanical breakers are considered mature and reliable, further research and understanding of arc physics would enable quicker detection of faults and fault locations. Hybrid switches, made from the combination of mechanical and solid-state devices, potentially provide faster interruption capabilities, which open opportunities for dynamic fault coordination. While these technologies are mature for HVAC applications, they are not as mature for HVDC applications. HVAC circuit breakers open during the zero crossing of voltage to minimize arcing, but no such crossing occurs in DC power flows, presenting unique design and reliability challenges. A full solid-state-based HVDC circuit breaker should be considered since advanced semiconductor devices are becoming available. For advanced multiterminal HVDC networks to be realized, reliable HVDC circuit breakers with matching power ratings are needed. Initial research has been conducted in electromechanical, solid-state, and hybrid DC circuit breakers. ABB has already developed a prototype for a hybrid HVDC breaker, which combines power electronic devices with a mechanical switch, but more research is needed to accelerate the development of this technology.[67] Material and design innovations can help drive down costs, increase power ratings, and accelerate technology deployment. In addition, MTDC networks require advanced methods for DC fault identification and location. Since many components within HVDC networks are located in isolated, and even undersea, locations, these enhancements will aid in system protection, maintenance, and restoration.

Fault Current Limiters

When faults occur, large currents (5 to 20 times nominal[68] with some claiming up to 200 times nominal) can develop. The maximum fault current in a system tends to increase over time due to increased loads and subsequent increase in generation, the existence of parallel conducting paths, more interconnections, and the addition of distributed generation.[70] The best way to handle a fault is with a device that can intercept the surge on an exceptionally short time frame, divert the high current until it dissipates, and then reset itself automatically without human intervention. Fault current limiters (FCLs) are devices that limit these excessive currents in transmission and distribution networks to manageable levels. They operate by rapidly inserting a large resistance or reactance to a line to absorb the excessive energy or limit the current. FCLs also decrease the required rating of the equipment they are protecting, alleviating the need for utilities to upgrade circuit breakers and substations to handle higher fault currents as the system evolves.

Superconducting fault current limiters (SFCLs) have the unique property of having little to no resistance in the superconducting state but quickly become resistive at the transition temperature. They also do not add impedance to the circuit during normal operation.[71] During fault conditions, the excess current heats the devices and triggers the transition. The DOE OE led R&D efforts in this technology. Various prototypes were developed, and the first SFCL in the U.S. electric grid was demonstrated in 2009. SFCL technology is starting to mature from R&D and demonstration projects into commercially available systems. Applied Materials recently announced a commercial order of two SFCLs to an independent power producer in Thailand and currently has an SFCL operating in New York.[72] The New York SFCL system has successfully limited 15 faults that could have resulted in service outages.[73] R&D efforts with SFCLs are still needed to reduce the cost of superconducting wire and refrigeration systems.[74] There are also power electronics-based FCLs that use semiconductor devices to insert the desired impedance during faults.

Surge Arresters

Increased use of power electronics-based controllers can increase power system susceptibility to lightning strikes, overvoltage, and other phenomena if appropriate protection schemes and technologies are not used. Surge arresters operate by providing a path to ground when an undesirable voltage is reached. The selection of arresters is coordinated with the insulation ratings of the equipment they are protecting so they can discharge the excess power before damage occurs.[75] Typical station class arresters are characterized by U_{pl}/U_r ratios of 2.5 at 20 kA_p lightning strikes.[76] This rating implies that power electronic-based systems will need to be built with significant overvoltage margins if typical arresters are used, thereby increasing system costs. Improving surge arresters with lower Upl/Ur ratios or more dynamic abilities can help lower costs for future grid transmission and distribution components that use semiconductor devices. A significant paradigm shift would need to be made for next-generation surge arresters with lower ratios to still function without allowing too much current through during switching events and still having temporary overvoltage capability to survive. However, more detailed analysis is required to investigate the feasibility of using new surge arresters on broader system protection.

Endnotes

[1] "Supply and Disposition of Electricity, 2002 through 2012." U.S. Energy Information Administration. Accessed March 6, 2015: http://www.eia.gov/electricity/annual/html/epa_01_03.html.

[2] Hellmuth, M.; Bruzgul, J.; Schultz, P.; Spindler, D.; Pacini, H. "Assessment of Climate Change Risks to Energy Reliability in the WECC Region." ICF International for the Western Electricity Coordinating Council, December 26, 2014. Accessed March 6, 2015: https://www.wecc.biz/_layouts/15/WopiFrame.aspx?sourcedoc=/Reliability/Assessment-of-Climate-Change-Risks-to-Reliability-ICF-Dec-2014.pdf&action=default&DefaultItemOpen=1.

[3] "Technology Performance Report #1—Irvine Smart Grid Demonstration: A Regional Smart Grid Demonstration Project." Southern California Edison, p. 70. Accessed March 6, 2015: https://www.smartgrid.gov/sites/default/files/doc/files/SCE-ISGD-TPR-1_Final.pdf.

[4] Age alone does not cause grid failure. Maintenance programs are designed to effectively monitor equipment condition and ensure that necessary improvements or replacements are implemented to ensure reliability.

[5] American Society of Civil Engineers. Failure to Act Economic Studies. Accessed March 6, 2015: http://www.asce.org/infrastructure_policy_reports/.

[6] "Large Power Transformers and the U.S. Grid." U.S. Department of Energy, Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability, April 2014. Accessed March 6, 2015: http://energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf.

[7] "Economic Benefits of Increasing Electric Grid Resilience to Weather Outages." Executive Office of the President, August 2013. Accessed March 6, 2015: http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf.

[8] American Society of Civil Engineers. Failure to Act Economic Studies. Accessed March 6, 2015: http://www.asce.org/infrastructure_policy_reports/.

[9] Hall, K. L. "An Updated Study on the Undergrounding of Overhead Power Lines." Hall Energy Consulting Inc., 2012. Accessed March 6, 2015: http://www.eei.org/issuesandpolicy/electricreliability/undergrounding/Documents/UndergroundReport.pdf.

[10] "Estimating the Costs and Benefits of the Smart Grid." EPRI, 2011. Accessed March 6, 2015: http://www.rmi.org/Content/Files/EstimatingCostsSmartGRid.pdf.

[11] "Transmission & Distribution Infrastructure." Harris Williams & Co., 2014. Accessed March 6, 2015: http://www.harriswilliams.com/sites/default/files/industry_reports/ep_td_white_paper_06_10_14_final.pdf?cm_mid=3575875&cm_crmid=e5418e44-29ef-e211-9e7f-00505695730e&cm_medium=email.

[12] "Transmission and Distribution Equipment and Systems: Facts and Figures." Newton-Evans Research Company, 2014. Accessed March 6, 2015: http://www.newton-evans.com/transmission-and-distribution-equipment-and-systems-facts-and-figures/.

[13] "Transmission & Distribution Infrastructure." Harris Williams & Co., 2014. Accessed March 6, 2015: http://www.harriswilliams.com/sites/default/files/industry_reports/ep_td_white_paper_06_10_14_final.pdf?cm_mid=3575875&cm_crmid=e5418e44-29ef-e211-9e7f-00505695730e&cm_medium=email.

[14] "Transmission and Distribution Equipment and Systems: Facts and Figures." Newton-Evans Research Company, 2014. Accessed March 6, 2015: http://www.newton-evans.com/transmission-and-distribution-equipment-and-systems-facts-and-figures/.

[15] "Electricity Transmission & Distribution White Paper." NRGExpert, 2013. Accessed March 6, 2015: http://www.nrgexpert.com/files/NRG%20Expert%20Electricity%20T&D%20White%20Paper.pdf.

[16] "World Energy Investment Outlook." International Energy Agency, 2014. Accessed March 6, 2015: http://www.iea.org/publications/freepublications/publication/weio2014.pdf.

[17] High Voltage Direct Current (HVDC) Network Update. MISO Energy, 2015. Accessed March 3, 2015: https://www.misoenergy.org/Events/Pages/HVDC20141016.aspx.

[18] "Large Power Transformers and the U.S. Grid." U.S. Department of Energy, Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability, April 2014. Accessed March 3, 2015: http://www.energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf.

[19] Distribution transformers covered by standard defined in the Code of Federal Regulations, 10 CFR 431.192. Accessed April 1, 2015: http://www.gpo.gov/fdsys/pkg/CFR-2012-title10-vol3/pdf/CFR-2012-title10-vol3%20sec431192.pdfhttp:/www.gpo.gov/fdsys/pkg/CFR-2011-title10-vol3/pdf/CFR-2011-title10-vol3-sec431-192.pdf.

[20] "Electric Power—Distribution Systems (Distribution Transformer)." U.S. Department of Labor. Accessed March 3, 2015: https://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/distribution_system/distribution_transformers.html.

[21] "Large Power Transformers and the U.S. Grid." U.S. Department of Energy, Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability, April 2014. Accessed March 3, 2015: http://www.energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf.

[22] "Power Transformers Built for Reliability and Efficiency." ABB. Accessed March 6, 2015: http://www05.abb.com/global/scot/scot252.nsf/veritydisplay/a2492a9e17a69c1a83257984002ada63/$file/Global_low%20res.pdf.

[23] "Large Power Transformers and the U.S. Grid." U.S. Department of Energy, Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability, April 2014. Accessed March 6, 2015: http://energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf.

[24] "Efficient Electrical Energy Transmission and Distribution." International Electrotechnical Commission. Accessed March 3, 2015: http://www.iec.ch/about/brochures/pdf/technology/transmission.pdf.

[25] "Development and Technology of HTS Transformers." Science Platform, Vol. 1, No. 1, December 2007. Accessed May 13, 2015: http://scienceplatform.com/RC/vol_1/P2.pdf.

[26] Baehr, R. "Transformer Technology State-of-the-Art and Trends of Future Development." Electra, Vol. 198, October 2001. Accessed March 3, 2015: http://www.vde.com/de/fg/etg/arbeitsgebiete/v2/documents/mcms/transformer.pdf.

[27] Chapter 3: Market and Technology Assessment. Office of Energy Efficiency & Renewable Energy (undated). Accessed March 6, 2015: https://www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/dist_trans_chp_3.pdf.

[28] Distribution Transformers. Office of Energy Efficiency & Renewable Energy. Accessed March 6, 2015: http://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/66.

[29] Rathod, D.K. "Solid State Transformer (SST) 'Review of Recent Developments.'" Advance in Electronic and Electric Engineering, ISSN 2231-1297, Vol. 4, No. 1, 2014; pp. 45-50. Accessed March 27, 2015: http://www.ripublication.com/aeee_spl/aeeev4n1spl_07.pdf.

[30] "Solid State (Smart) Transformer Market Is Expected to Reach $5,043.39 Million at a CAGR of 82.3% by 2020—New Report by Markets and Markets." PRWeb, February 23, 2013. Accessed March 3, 2015: http://www.prweb.com/releases/solid-state-smart/transformer-market/prweb10458931.htm.

[31] Gangyao et al. "Comparisons of 6.5 kV 25A Si IGBT and 10-kV SiC MOSFET in Solid-State Transformer Application." Energy Conversion Congress and Exposition (ECCE), IEEE, 2010.

[32] "The Next Generation of Power Conversion Systems Enabled by SiC Power Devices." Rohm Semiconductor White Paper. Accessed March 3, 2015: http://www.rohm.com/documents/11308/f75d744e-efd3-480e-9c96-34e7db3fad9d.

[33] FREEDM Systems Center. Accessed March 3, 2015: http://www.freedm.ncsu.edu/index.php?s=1.

[34] Huang et al. "Next Generation Power Distribution System Architecture: The Future Renewable Electric Energy Delivery and Management (FREEDM) System." Energy 2013: The Third International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies. Accessed March 3, 2015: www.thinkmind.org/download.php?articleid=energy_2013_2_40134.pdf.

[35] "Next Generation Electrical Transformer Helps Lay Foundation for Smart Grid." National Science Foundation, 2013. Accessed March 3, 2015: http://erc-assoc.org/achievements/next-generation-electrical-transformer-helps-lay-foundation-smart-grid.

[36] Hauer, J.; Overbye, T.; Dagle, J.; Widergren, S. "Advanced Transmission Technologies." Accessed March 3, 2015: http://certs.lbl.gov/ntgs/issue-6.pdf.

[37] Hall, K. L. "An Updated Study on the Undergrounding of Overhead Power Lines." Hall Energy Consulting Inc., 2012. Accessed March 6, 2015: http://www.eei.org/issuesandpolicy/electricreliability/undergrounding/Documents/UndergroundReport.pdf.

[38] Replacement of cable or wire on an electric circuit, typically a high-voltage transmission line, to afford a greater electric-current-carrying capability.

[39] "New Power Cable Technology Launched at AEP's Bixby Station." American Electric Power. Accessed May 13, 2015: http://www.aep.com/newSroom/newSreleaSeS/Default.aspx?id=1302.

[40] Independent Statistic & Analysis—U.S. Energy Information Administration. Accessed April 2, 2015: http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3.

[41] Tian, A., et al. "Prospects for Novel Deformation Processed Al/Ca Composite Conductors for Overhead High Voltage Direct Current (HVDC) Power Transmission." Electric Power Systems Research, Vol. 105, pp. 105-114; 2013.

[42] Hjortstam, O.; Isberg, P.; Söderholm, S.; Dai, H. "Can We Achieve Ultra-Low Resistivity in Carbon Nanotube-Based Metal Composites?" Applied Physics A, Vol. 78, Issue 8, pp. 1175-1179; 2004.

[43] "Advanced Transmission Hardware." Prepared by Black & Veatch. Western Interstate Energy Board, 2013. Accessed March 6, 2015: http://www.westernenergyboard.org/sptsc/documents/06-05-13athc.pdf.

[44] "Superconductivity Power Equipment." Office of Electricity Delivery and Energy Reliability, July 14, 2009. Accessed March 3, 2015: http://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/HTS_cable_project_07.14.09.pdf.

[45] "Program on Technology Innovation: A Superconducting DC Cable." Electric Power Research Institute. Accessed May 13, 2015: http://www.epri.com/abstracts/pages/productabstract.aspx?ProductID=000000000001020458.

[46] "A National Effort to Introduce New Technology into the Power Delivery Infrastructure." Office of Electricity Delivery and Energy Reliability. Accessed May 13, 2015: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/cable_overview2.pdf.

[47] Sytnikov, V. E. "HTS Cable Projects in Russia." R&D Center at Federal Grid Company United Energy System, International Superconductivity Industry Summit Moscow, Russian Federation; November 12-14, 2014.

[48] Templeton, G. "World's First Superconducting Power Line Paves the Way for Billions of Dollars in Savings, More Nuclear Power Stations." May 14, 2014. ExtremeTech. Accessed on March 3, 2015: http://www.extremetech.com/extreme/182278-the-worlds-first-superconducting-power-line-paves-the-way-for-billions-of-dollars-in-savings.

[49] Plus-minus corresponds to -350 kV/+350 kV.

[50] Whicker, D. R. “Before Lines Fall Down.” Transmission and Distribution World. Classic Connectors, 2010. Accessed March 6, 2015: http://classicconnectors.com/downloads/Before_Lines_Fall_Down.pdf.

[51] For example, in the western part of the United States, the average transmission line and transformer loading for the Western Electricity Coordinating Council (WECC) 2023 HS1 BASE CASE released by WECC Transmission Expansion Planning Policy Committee is 31%.

[52] “Congestion and Marginal Losses.” Monitoring Analytics, LLC. PJM, 2012. Accessed March 3, 2015: http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2012/2012q1-som-pjm-sec10.pdf.

[53] Tolbert, L. M., et al. “Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications.” ORNL/TM-2005/230. Oak Ridge, TN: Oak Ridge National Laboratory, December 2005. Accessed March 3, 2015: https://www.smartgrid.gov/sites/default/files/doc/files/Power_Electronics_for_Distributed_Energy_Systems_Transmissio_200508.pdf.

[54] “HVDC-VSC: Transmission Technology of the Future.” Alstom Grid, Spring-Summer 2011, pp. 13-17. Accessed March 3, 2015: http://www.alstom.com/Global/CleanGrid/Resources/Documents/HVDCVSC%20transmission%20technology%20of%20the%20future%20-%20Think%20Grid%20n%C2%B08%20.pdf.

[55] Rudervall, R., et al. “High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper.” Energy Week 2000, Washington, DC, March 7-8, 2000. Accessed April 8, 2015: http://library.abb.com/global/scot/scot221.nsf/veritydisplay/9e64dab39f71129bc1256fda004f7783/$File/Energyweek00.pdf.

[56] “Plains and Eastern Clean Line Transmission Project Draft Environmental Impact Statement.” Department of Energy, December 2014. Accessed March 3, 2015: http://www.energy.gov/sites/prod/files/2014/12/f19/EIS-0486-DEIS-Summary-2014.pdf.

[57] High Voltage Direct Current (HVDC) Network Update. MISO, 2014. Accessed April 10, 2015: https://www.misoenergy.org/Events/Pages/HVDC20141016.aspx.

[58] “Assessment and Analysis of the State-of-the-Art Electric Transmission Systems with Specific Focus on High-Voltage Direct Current (HVDC), Underground or Other New or Developing Technologies.” Alberta Energy, 2009. Accessed on March 6, 2015: http://www.energy.alberta.ca/electricity/pdfs/transmissionsystemsstudy.pdf.

[59] Koropatnick, R.L. “HVDC Projects Listing Prepared for the HVDC and Flexible AC Transmission Subcommittee of the IEEE Transmission and Distribution Committee.” March 2012. Accessed March 6, 2015: http://www.ece.uidaho.edu/hvdcfacts/Projects/HVDCProjectsListingMarch2012-existing.pdf.

[60] “Transmission and Distribution Networks: AC versus DC.” Spain: Department of Electrical Engineering, University of the Basque Country—Bilbao, 2014. Accessed March 6, 2015: http://www.researchgate.net/publication/228622198_Transmission_and_Distribution_Networks_AC_versus_DC.

[61] “Flexible AC Transmission: The FACTS Machine, Top 11 Technologies of the Decade.” IEEE Spectrum, 2010. Accessed March 6, 2015: http://spectrum.ieee.org/energy/the-smarter-grid/flexible-ac-transmission-the-facts-machine.

[62] “Advanced Transmission Hardware.” Prepared by Black & Veatch. Western Interstate Energy Board, 2013. Accessed March 6, 2015: http://www.westernenergyboard.org/sptsc/documents/06-05-13athc.pdf.

[63] Cai, L. J., et al. “Optimal Choice and Allocation of FACTS Devices Using Genetic Algorithms.” Power Systems Conference and Exposition, IEEE PES, October 10-13, 2004. Accessed March 6, 2015: https://www.uni-due.de/ean/downloads/papers/isap03-068.pdf.

[64] “Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications.” U.S. Department of Energy, 2005. Accessed March 6, 2015: http://web.eecs.utk.edu/~tolbert/publications/ornl_tm_2005_230.pdf.

[65] Divan, D.; Johal, H. “Distributed FACTS—A New Concept for Realizing Grid Power Flow Control.” IEEE Transactions on Power Electronics, Vol. 22, No.6, November 2007. Accessed March 6, 2015: http://paginas.fe.up.pt/~ee04109/Documentos%20e%20imagens/59%20%20Distributed%20FACTS_A%20New%20Concept%20for.pdf.

[66] “Magnetic Amplifier for Power Flow Control.” ARPA-E Energy. Accessed March 6, 2015: http://arpa-e.energy.gov/?q=slick-sheet-project/magnetic-amplifier-power-flow-control.

[67] Callavik, M., et al. “The Hybrid HVDC Breaker.” ABB. Accessed March 6, 2015: http://www.abb-conversations.com/2012/11/abb-achieves-another-milestone-in-electrical-engineering/.

[68] “Superconducting Fault Current Limiters.” EPRI, 2009. Accessed March 6, 2015: http://www.smartgridnews.com/artman/uploads/1/000000000001017793.pdf.

[69] “Applied Materials Teaming with Central Hudson Gas & Electric to Demonstrate Superconducting Fault Current Limiter Technology in New York.” Applied Materials, 2014. Accessed March 6, 2015: http://www.appliedmaterials.com/company/news/press-releases/2014/04/applied-materials-teaming-with-central-hudson-gas-electric-to-demonstrate-superconducting-fault-current-limiter-technology-in-new-york.

[70] “Superconducting Fault Current Limiters.” EPRI, 2009. Accessed March 6, 2015: http://www.smartgridnews.com/artman/uploads/1/000000000001017793.pdf.

[71] “High-Temperature Superconductivity for Electric Systems.” U.S. Department of Energy, 2009. Accessed March 6, 2015: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/Supercon_Overview_Fact_Sheet_7_14_09.pdf.

[72] “Applied Materials Receives Order for Two Transmission-Class Superconducting Fault Current Limiters.” Applied Materials. Accessed March 3, 2015: http://www.appliedmaterials.com/company/news/press-releases/2015/04/applied-materials-receives-order-for-two-transmission-class-superconducting-fault-current-limiters.

[73] "Innovative Superconducting Technology Providing Benefits." Central Hudson. April 3, 2015. Accessed March 3, 2015: http://www.centralhudson.com/news/news/april3_2015.html.

[74] "Superconductivity & Solid-state Power Equipment." Office of Electricity Delivery and Energy Reliability, 2009. Accessed March 3, 2015: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/hts_fcl_110609.pdf.

[75] Pryor, L. "The Application and Selection of Lightning Arresters." GE Industrial. Accessed March 6, 2015: http://apps.geindustrial.com/publibrary/checkout/Arresters?TNR=White%20Papers|Arresters|generic.

[76] Simplified Arrester Selection Procedure. ABB. Accessed March 6, 2015: https://library.e.abb.com/public/837fb693e1d19a1dc1257b130057b22a/Buyers%20guide%20Selection%20(C).pdf.

[77] [1] Tian L, Anderson I, Riedemann T, Russell A, Kim H. Electr Pow Syst Res 2013;105:105. [2] Russell AM, Lund T, Chumbley LS, Laabs FA, Keehner LL, Harringa JL. Compos Part A-Appl S 1999;30:239. [3] Tian L, Russell A, Anderson I. J Mater Sci 2014;49:2787.

Glossary and Acronyms

Advanced Metering Infrastructure (AMI)	An integrated system of smart meters, communications networks, and data management systems that enable two-way communication between utilities and customers.
ASCE	American Society of Civil Engineers
DOE	U.S. Department of Energy
Edison Electric Institute (EEI)	An association that represents the interests of U.S. shareholder-owned electric utilities.
Electric Power Research Institute (EPRI)	A nonprofit organization that conducts research, development and demonstration (RD&D) relating to the electric power sector.
Fault current limiter (FCL)	A FCL limits excessive current from flowing through the system and allows for the continual, uninterrupted operation of the electrical system.
Flexible alternating current transmission system (FACTS)	A power electronic-based system that provides control of one or more transmission system parameters in an AC grid.
Future renewable electric energy delivery and management (FREEDM) Center	The FREEDM System Center was founded by the National Science Foundation in 2009 to promote innovation technologies in power distribution.
High temperature superconductors (HTS)	Materials that display superconducting properties at temperatures above that of liquid nitrogen.
High temperature-low sag (HTLS)	Conductors in which the inner core material carries all the tension, and the aluminum wires carry almost all the current. Consequently, the conductor can carry more current while sagging less at higher operating temperatures.
High-voltage, direct current (HVDC)	A system that uses high voltage DC for bulk transmission of electrical power.
Insulated-gate bipolar transistor (IGBT)	A device that is primarily used as an electronic switch for power flows.
Interline power flow controller (IPFC)	A concept for the compensation and effective power flow management of multi-line transmission systems.
International Electrotechnical Commission (IEC)	A non-profit, non-government international standards organization that prepares and publishes standards for all electrical, electronic and related technologies.
KWh (kilowatt-hour)	A measure of electrical energy.
Large power transformer (LPT)	A power transformer is device used for transforming power (i.e., voltage levels) from one circuit to another without changing the frequency. LPT is broadly used to describe a power transformer used in bulk power systems.

Line-commutated convertors (LCC)	A type of HVDC converter technology that relies on the line voltage of an AC system (i.e., line-commutated) for the conversion process.
Magnetic amplifier power flow controller (MAPFC)	A common electromagnetic device used in electronic applications such as power flow control.
Metal oxide semiconductor field-effect transistor (MOSFET)	A metal oxide based semiconductor device used for amplifying or switching electronic signals.
MVA/kVA	Mega/kilo volt-ampere; both are units of apparent power.
MVAR/kVAR	Mega/kilo volt ampere reactive; both are units of reactive power.
National Science Foundation (NSF)	An independent U.S. government agency responsible for promoting science and engineering through research programs and projects.
PJM	A regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of 13 states and the District of Columbia in the U.S Northeast.
PPL	Polypropylene paper laminate.
Recovery Transformer (RecX)	One of the federal initiatives by SmartGrid.gov . The goal of this program is to increase the resilience of the nation's electric transmission grid by drastically reducing the recovery time associated with transformer outages. The first prototype transformer was designed by the RecX consortium and is now installed at a CenterPoint Energy substation for testing.
Solid State Transformers (SST)	A collection of high-powered electronic circuits and semiconductor components that is capable of supplying power at requisite frequency and voltage. Unlike conventional transformers, SSTs do not rely on electromagnetic induction for voltage step-up/step-down.
Unified Power Flow Controller (UPFC)	A device that is capable of controlling voltage magnitude, active and reactive power flows.
Voltage source converter (VSC)	An electric power convertor which changes the voltage of an electrical power source. It is used in HVDC convertor technology.
XPLE	High density cross-linked polyethylene.