MATERIALS INNOVATION FOR NEXT GENERATION T&D GRID COMPONENTS

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CONTENTS

1. INTRODUCTION

Reliable, affordable, secure, and clean electric power underpins national priorities such as economic growth, public health and safety, and environmental quality. However, the electric grid is being operated in ways for which it was not originally designed, which has the potential to impact these priorities. Current trends facing the electric power system include:

- **Changing demand** driven by population growth, adoption of energy efficient technologies, dynamic economic conditions, more active consumer participation with distributed energy resources, and broader electrification, including possible mass-markets for electric vehicles
- **Changing supply mix** (e.g. renewable, nuclear, natural gas, coal) and location (centralized, distributed, off-shore) of the nation's generation portfolio driven by technology, market, and policy developments
- **Increasing variability** and uncertainty from supply and demand changes, including the integration of variable renewables, more active consumer participation, and accommodating new technologies and techniques
- **Increasing threats** to the reliability and security of the electric infrastructure (e.g. more frequent and intense extreme weather events, cyber threats and attacks, interdependencies with natural gas and water)
- **Aging electricity infrastructure** that requires new technologies to enable better failure detection, upgrade capabilities, and improve cybersecurity

The result of these trends is a system that is under increasing stress and requires much greater flexibility, agility, and ability to dynamically optimize grid operations. Additionally, there is a need for increased resiliency, interoperability, and adaptability to accommodate growing uncertainty. These trends present challenges as well as opportunities to advance the capabilities of today's electricity delivery system. During this period of transition, the deployment of new technologies will play a critical role in shaping the future grid.

PURPOSE

This document attempts to provide a high level overview of the current status of key grid components and highlights some innovative materials for use in these components. Research and development (R&D) of next-generation grid components has the potential to address challenges associated with the trends and accelerate grid modernization efforts. Advances in next-generation technologies will also need to consider the manufacturability of the component to manage costs and ensure scalability.

Section 2 provides an overview of critical transmission and distribution components, their function in the electric grid, and examples of challenges they face for increased flexibility and resilience and reduced cost. These components include transformers, flexible alternating current transmission (FACTS) devices, high voltage direct current (HVDC) converters, cables and conductors, protection devices (e.g., breakers and fault current limiters), and other substation components.

Section 3 contains examples of innovative materials that have the potential to improve the fundamental properties and capabilities of hardware for transmission and distribution components. These innovative materials are categorized into several functional areas such as active power conversion (i.e., semiconductors), passive power conversion (i.e., magnetics), electrical insulation, electrical conduction, structural support and protection, and thermal management.

Figure 1.1 illustrates the relationship between functional materials that form the basis of transmission and distribution components and their role in an evolving electric power system. Materials innovation can enhance grid components to address emerging system trends; simultaneously, system trends change grid component requirements that may require new material innovations.

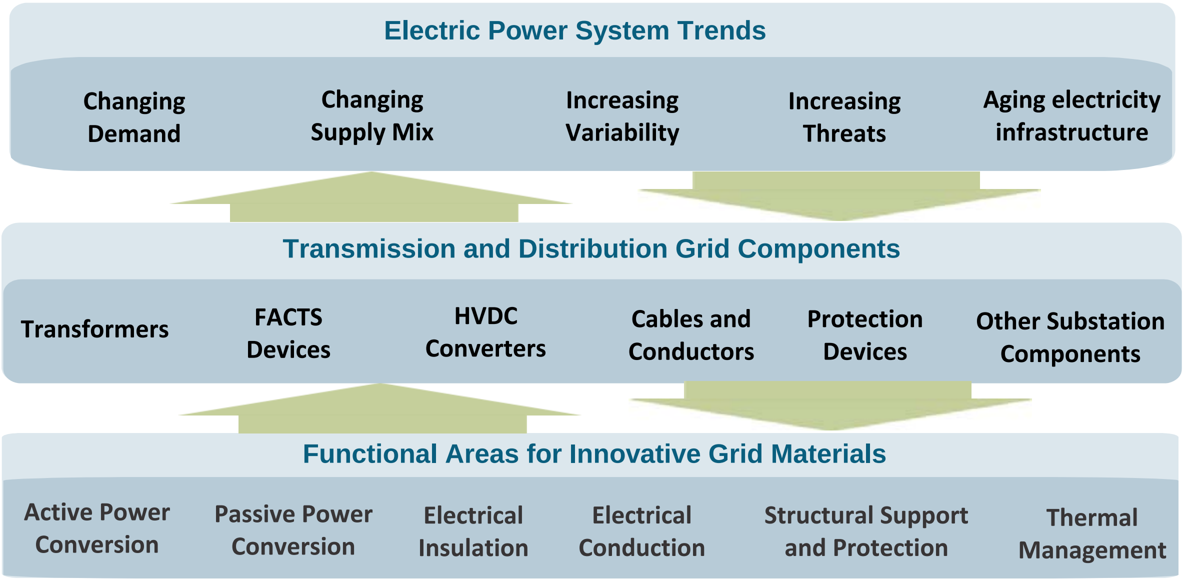

Figure 1.1. Connection between functional areas for innovative grid materials, T&D grid components and electric power system trends.

2. SUMMARY OF T&D GRID COMPONENTS

Transmission and distribution components include transformers, FACTS devices, HVDC converters, cables and conductors, protection devices, and other substation equipment. Other components and systems used in the generation and end use of electricity, as well as energy storage systems, are not included in this paper. Each summary contains background information about the components; their functionality in the grid; cost and market data, where available; and R&D challenges.

TRANSFORMERS

Transformers are essential to the transmission and distribution of electricity efficiently and reliably. Their most important function is transforming voltage levels, stepping them up for long-distance transmission from a power plant, and stepping them down for distribution to consumers. This basic physical principle of transformers is still the same today as it was 130 years ago, but energy density, efficiency, costs, weight and dimensions have dramatically improved.

COMPONENT ANALYSIS

The United States is one of the world's largest markets for power transformers, with an estimated market value of more than $1 billion in 2010, or almost 20 percent of the global market.[1] The estimated number of large power transformers installed in the United States is unavailable; however, the number could be in the range of tens of thousands. The number of extra high voltage large power transformers is approximately 2,000. The classes for transformers range from distribution voltages of 2.5 kV to extra high voltages up to 765 kV.[2]

Transformer Voltage Classes

- Distribution voltage, 2.5-35 kV
- Medium voltage, 34.5-115/138 kV
- High voltage, 115/138-230 kV
- Extra High voltage, 345-765 kV

Transformers are being operated beyond their designed lifetime. For instance, approximately 70% of transformers are over 25 years old; while their useful life is estimated to be approximately 20 years.[3]

A transformer in its most basic form consists of two inductive windings and a laminated steel core. The windings are made of copper conductors wound around the core, providing electrical input and output. The core is made of high-permeability, grain-oriented, silicon electrical steel, layered in pieces. The coils are insulated from each other as well as from the steel core.

The raw materials cost is significant, accounting for 57 to 67 percent of the total cost of a typical Large Power Transformer (LPT) sold in the United States between 2008 and 2010. Of the total material cost, the largest cost is the special grade electrical steel for the transformer core, then the copper windings, then the press board and paper, bushings and oil. Approximately 18 to 27 percent is for copper windings and 22 to 24 percent is for electrical steel for the transformer core.[4] In 2010, the approximate cost of a LPT with an MVA rating between 75 MVA and 500 MVA was estimated to range from $2 to $7.5 million in the United States.[5] However, these estimates were Free on Board (FOB) factory costs, exclusive of transportation, installation, and other associated expenses, which generally add 25 to 30 percent to the total cost, given its large dimensions and weight.

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[1] http://electrical-engineering-portal.com/an-overview-of-large-power-transformer-lpt, *accessed August 14, 2015*

[2] U.S. DOE Report, Large Power Transformers and the U.S. Electric Grid, June 2012

[3] Harris Williams & Co. Transmission & Distribution Infrastructure, Summer 2014 http://www.willis.com/documents/publications/services/property/Transformer_Problem.pdf, *accessed August 14, 2015*

[4] "Large Power Transformers from Korea," USITC, Preliminary Investigation, September 2011, p. V-1.

[5] Large Power Transformers and the US Electric Grid, Update, U.S. DOE 2014

CHALLENGES

Table 2.4 Challenges of Transformers

Aging infrastructure. The transformers are being operated beyond their designed lifetimes.
Cost. LPTs are custom-designed equipment that entails a significant capital expenditure and a long lead time due to an intricate procurement and manufacturing process.
Large dimensions and weight. There are constraints where the transformer can be located and how it can be transported because of its size and weight. The space and transportation problem will only grow worse as the size of the equipment expands to meet growing load demand.
Environmental concerns. The environmental impacts of transformers can affect where they can be located. They can have long-lasting impacts on noise, land use changes, habitat loss, and public safety etc.[6] The oil used for cooling transformers has the potential for leakage into the ground.
No-load losses. No-load losses result from resistance in the transformer's laminated steel core.
Load losses. Heat losses in the winding materials contribute the largest part of the load losses.[7] They are created by resistance of the conductor to the flow of current or electrons.
Cooling systems. It is essential to control the temperature with in permissible limit to ensure the long life of transformer by reducing thermal degradation of its insulation system.
Difficulty in replacing energized components. Transformers are not designed to easily be able to replace components, such as bushings, while device is partially energized or de-energized for a short period of time.
Increased system dynamics. Increased system dynamics and harmonics may lead to higher rates of failure.
Electrical disturbances. Electrical disturbances such as switching surges, voltage spikes, line faults/flashovers, and other utility abnormalities, excluding lightning, are responsible for approximately 28% of failures.[8]
Load tap changer failure. Load tap changers have been a weak link in many networks as they deteriorate over time due to mechanical problems or contact wear from repeated operations.
Security issue. Security enhancements should be embedded into the physical design of LPTs. Resistance to geomagnetically induced currents, electromagnetic pulses, and physical attacks should be incorporated into LPT designs. The oil used to cool transformers has a flammability risk.
Materials for advanced designs. Limitations for solid state transformers are related to the magnetic materials used in design due to losses at increasing switching frequencies and behavior at higher temperatures.

FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS) DEVICES

FACTS refer to a family of power electronics-based devices able to enhance AC system controllability and stability and to increase power transfer capability. They are combinations of solid state switches and

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[6] Environmental Impacts of Substations, Public Service Commission of Wisconsin.

[7] http://www.copper.org/environment/sustainable-energy/transformers/education/trans_losses.html, *accessed August 14, 2015*

[8] Bartley, William H., "Analysis of Transformer Failures," Hartfort Steam Boiler Inspection & Insurance Co., 79th International Conference of Doble Clients, March 25 – 30, 2012, Boston, MA.

computerized automation that enable nearly instantaneous customized control of AC power flows, far faster than traditional, electromechanical AC switches.

FACTS technology offers ways to modify the electrical characteristics of the transmission system more rapidly, even in real time, so as to increase operating efficiency and relieve constraints without the need for adding major new hardware or upgrades. FACTS devices can perform a number of functions including reactive compensation, phase shifting and power flow control.[9]

There are two main types of FACTS technologies based on the power semiconductor switches used, including thyristor controlled devices and voltage sourced converters. Examples of thyristor controlled devices include Static VAr Compensators (SVC) and Thyristor-Controlled Series Capacitors (TCSC). Voltage-sourced converters (VSC) based devices include Synchronous Static Compensator (STATCOM) and Universal Power Flow Controllers (UPFC). Another type of FACTS device is a fixed series capacitor (FSC).[10]

COMPONENT ANALYSIS

The value of the FACTS market was approximately $912 million in 2012, and is expected to reach $1,386 million in 2018. Key market drivers include growing power quality and network reliability requirements, upgradation and replacement of aging power infrastructure, increasing efficiency and environmental regulations and high cost involvement in building new transmission lines.[11] Other market research forecasts that global cumulative FACTS installation revenue will amount to $42 billion between 2014 and 2023.[12] Static VAr Compensators (SVC) represents the first generation of FACTS devices, and accounted for the largest percentage of the overall market revenue in 2012. The SVC market is projected to reach $966.70 million by 2018. STATCOM and TCSC are some of the other major contributors to the overall market revenue.[13]

The investment costs of FACTS devices can be broken down into two categories: (1) the equipment cost, and (b) the infrastructure cost. Figure 2.1 shows the cost breakdown for a typical FACTS installation comparing thyristor-based with converter-based systems. Converter-based systems have more capabilities than thyristor-based systems, and are generally more expensive. The equipment cost includes solid-state devices, magnetic component, auxiliary component and passive component costs. The infrastructure cost is mainly field construction.

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[9] Electric Power Systems: A Conceptual Introduction, *Alexandra Von Meier,* 2006

[10] FACTS Solutions to Optimize Network Performance, Alstom, 2010

[11] http://www.marketsandmarkets.com/PressReleases/flexible-ac-transmission-system.asp, *accessed August 14, 2015*

[12] Navigant Research market forecasts revolve around Series Compensation, SVCs, STATCOMs, and emerging D-SVC/D-STATCOM installations for specific technical applications, July 2014.

[13] http://www.marketsandmarkets.com/PressReleases/flexible-ac-transmission-system.asp, *accessed August 14, 2015*

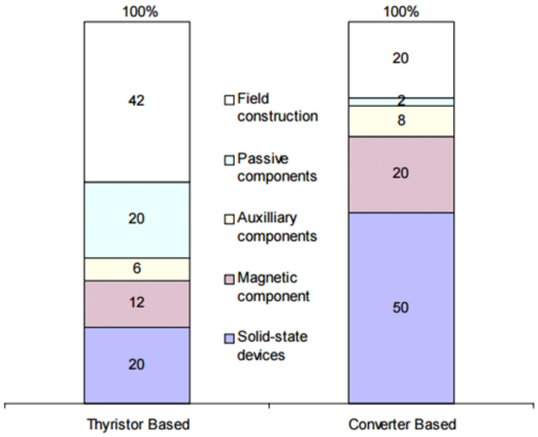
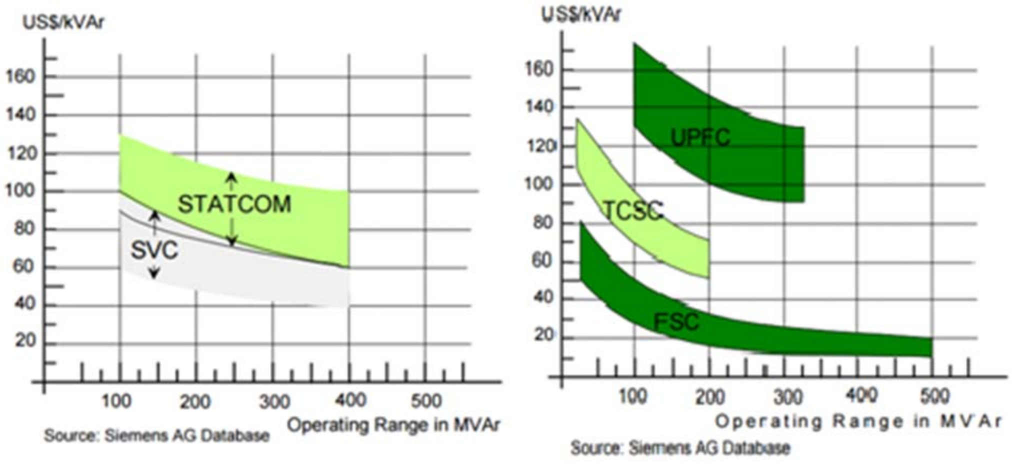


Figure 2.1 Cost Breakdown of FACTS Devices[14]

Infrastructure costs depend on the substation location, where the FACTS device should be installed. These costs include land acquisition, if there is insufficient space in the existing substation; modifications in the existing substation, e.g. if new HV switchgear is required; construction of a building for the indoor equipment (control, protection, thyristor valves, auxiliaries etc.); yard civil works (grading, drainage, foundations etc.); and connection of the existing communication system with the new installation. Other costs include installation, commissioning, insurance, and project management etc.

For typical devices' ratings, the lower limit of the cost areas shown in Figure 2.2 indicates the equipment costs, and the upper limit indicates the total investment costs including the infrastructure costs. The cost per kVAr decreases for higher capacity of FACTS devices due to economies of scale. The total investment costs shown, which are exclusive of taxes and duties, may vary due to the described factors by –10% to +30%. Including taxes and duties, which differ significantly between different countries, the total investment costs for FACTS devices may vary even more.[15]



Source: Siemens AG Database

Source: Siemens AG Database

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[14] Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications, Oak Ridge National Laboratory, 2005.

[15] Habur, K. and D. O'Leans, 2004. FACTS-flexible alternating current transmission systems: For cost effective and reliable transmission of electrical energy. http://www.rds.ontarioenergyboard.ca/WEBDRAWER/WEBDRAWER.DLL/webdrawer/rec/176620/view/Pappas_EVD_Set%201_Part%202_facts_siemens_20080411.PDF, *accessed August 14, 2015*

Figure 2.2 Typical Investment Costs for FACTS devices[16]

Unlike new overhead transmission lines that take several years to construct, FACTS installation requires only 12 to 18 months. FACTS installation has the flexibility for future upgrades and requires small land area.

Depending on the type and rating of the selected device and on the specific voltage level and local network conditions, a transmission capacity enhancement of up to 40-50 percent may be achieved by installing a FACTS element. In comparison to traditional mechanically-driven devices, FACTS controllers are also not subject to wear and require lower maintenance. However, as compared to conventional devices, FACTS controllers are very expensive because of semiconductor devices. See Table 2.5 for a general comparison of conventional versus thyristor based and VSC based controllers.

Table 2.5 Comparison of Conventional and FACTS Control Devices

	Conventional Devices	Thyristor-Based FACTS	Voltage Source Converter-Based FACTS
Response Speed	Slow to medium	Fast	Ultrafast
Switching	Limited	Unlimited	Unlimited
Output	Stepped	Continuous smooth	Continuous smooth
Cost	Less Expensive	More expensive	Even more expensive

CHALLENGES

Table 2.6 Challenges of FACTS Devices.

Cost. FACTS devices are 5 to 10 times more costly than conventional devices.
Procurement Availability. Very limited competition exists regarding the procurement of TCSC and STATCOM. For the case of UPFC, it is more likely that there will be no competition at all.
High Losses. More effort is needed in the development of semiconductor switches that are fast, and have low switching and conduction losses.
Reliability. Power semiconductor switch techniques need to be advanced through application of simplified circuits and advanced packaging techniques to improve reliability.
Size. Large size increases costs and decreases mobility and relocatability for desired performance. Modular and scalable designs are needed to make system expansion more simple and feasible. High frequency transformers can be used to reduce the size and cost of the system.

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[16] Habur, K. and D. O'Leans, 2004. FACTS-flexible alternating current transmission systems: For cost effective and reliable transmission of electrical energy. http://www.rds.ontarioenergyboard.ca/WEBDRAWER/WEBDRAWER.DLL/webdrawer/rec/176620/view/Pappas_EVD_Set%201_Part%202_facts_siemens_20080411.PDF, *accessed August 14, 2015*

HVDC CONVERTERS

The unique capability of HVDC converters is that they can connect two systems with different operating frequencies or different frequency controls. This technology is usually deployed as a back-to-back station or a point-to-point connection where a large amount of power has to be transmitted.[17]

HVDC converters are not a stand-alone technology. Generally, a HVDC system consists of two converter stations with a DC line between them. Depending on the configuration, the converter stations can operate as rectifiers converting AC to DC or as inverters converting DC to AC. This is done by means of high-power, high-voltage electronic semiconductor valves and in many cases the power electronics converters can benefit from a high frequency transformer for galvanic isolation. HVDC converters are divided into two main categories: line-commutated converters (LCC) are made with electronic switches that can only be turned on while voltage-sourced converters (VSC) are made with switches that can be turned both on and off. Worldwide there have been more than 100 LCC systems installed, totaling almost 55 GW of transmission capacity, and several more are under construction.[18]

COMPONENT ANALYSIS

HVDC is used to transmit electricity over long distances by overhead transmission lines or submarine cables when it becomes economically attractive over a conventional AC transmission lines. The cost comparison of DC and AC systems are shown in Figure 2.3. Typically, a HVDC transmission system has a rated power of more than 100 MW, and many are in the 1000 to 3000 MW range.

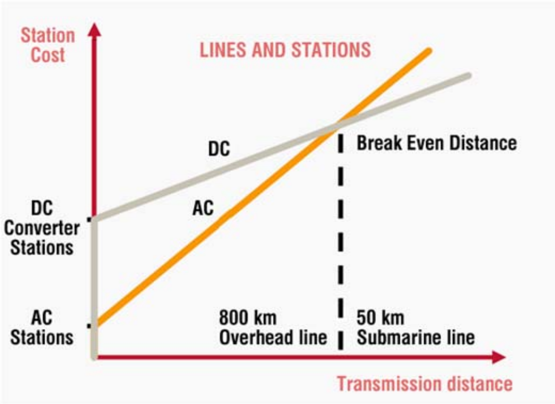

Figure 2.3 Cost Comparison of HVDC & AC Transmission Costs[19]

The cost of an HVDC transmission system depends on many factors, such as: Power capacity to be transmitted; Type of transmission medium; Environmental conditions and other safety, regulatory requirements etc.

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[17] A. Sumit Kumar Sah. FACTS and HVDC Technologies for the Development and Enhancement of Future Power Systems

[18] Koldby, E., Hyttinen, Mats., Challenges on the Road to an Offshore HVDC Grid, Nordic Wind Power Conference 2009

[19] http://electrical-engineering-portal.com/analysing-the-costs-of-high-voltage-direct-current-hvdc-transmission, *accessed August 14, 2015*

The options available for optimal design (different commutation techniques, variety of filters, transformers etc.) render it difficult to give a cost figure for an HVDC system. Nevertheless, a typical cost structure for converter stations is indicated in Figure 2.4.

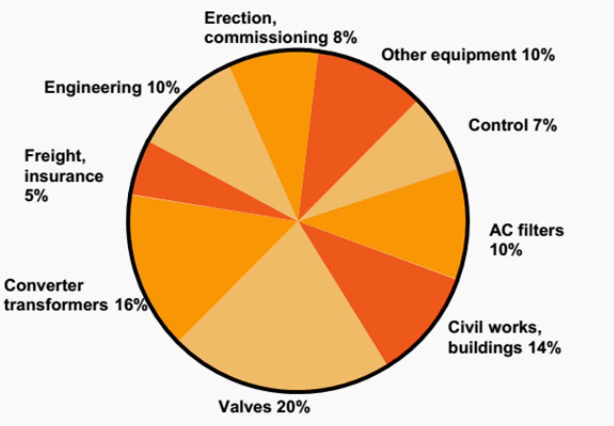

Figure 2.4 Typical Cost Structure of HVDC Stations

CHALLENGES

Table 2.7 Challenges of HVDC Systems

Cost. For shorter distances the capital cost is greater than AC systems.
Redundancy. In the traditional systems there has been a large degree of redundancy in the semiconductor valves, in the cooling systems and in the control system.
Standardization. Some standardization is necessary to integrate first generation DC systems in a future HVDC grid. For an offshore HVDC grid the types of HVDC converter and DC voltage needs to be standardized.
DC Circuit Breakers. In a large interconnected system, DC switches must be able to clear momentary faults. The interruption of DC has been a challenge since the very first point-to-point LCC transmission systems.
Protection Speed. The challenge is to measure voltage and current in a fast and reliable way. There is little to no service experience indicating the reliability of different proposed protection principles.

CABLES AND CONDUCTORS

Cables, conductors, and their connectors are as fundamental as transformers to the electricity delivery system. These components form the backbone of the grid, carrying power generated from centralized and distributed sources, along designated rights-of-way and distribution feeders, to customers. The U.S. Energy Information Administration (EIA) estimates that 6% of all electricity generated in the United States is lost in transmission and distribution equipment.[20] These technologies can be improved by leveraging material advances and improved designs.

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[20] U.S. Energy Information Administration, “Frequently Asked Questions: How much electricity is lost in transmission and distribution in the United States?” http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3, *accessed August 14, 2015*

COMPONENT ANALYSIS

From 2000 to 2010, US electric utilities invested more than $74.8 billion on transmission systems alone as population growth and aging infrastructure drove increased energy demand. Estimates show that $275 Billion worth of transmission cable will be needed globally between 2010 and 2019.

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 2.8. 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.

UNDERGROUND CABLES

Underground power cables mainly consist of a conductor, insulation, bedding, braiding/armouring and outer sheath. The insulation around the conductor is made of PVC, XLPE, and rubber.[21] The power capability of the cables of higher voltage classes is limited by the highest possible temperature insulation.[22] The estimated cost for constructing underground transmission lines ranges from 4 to 14 times more expensive than overhead lines of the same voltage and same distance.

High-temperature superconducting cables have been demonstrated as an alternative to copper cables for electric power transmission in urban settings and compact spaces. One superconducting cable could replace more than 10 copper cables, cutting weight by over 95 percent and eliminating heating loss.

OVERHEAD CONDUCTORS

Overhead transmission lines are typically aluminum conductors reinforced with steel for added strength and are designed to operate at rated power/thermal levels. The selection of the optimum conductor type and size for a given line consists of finding the conductor with the best economics. The major cost components of a transmission line depend upon conductor physical, mechanical and electrical parameters. A list of these basic parameters are: conductor diameter; weight per unit length; conductivity of material(s); cross-sectional area(s); modulus of elasticity; rated breaking strength; coefficient(s) of thermal expansion; cost of material(s); maximum unloaded design tension; resistance to vibration and/or galloping; surface shape/drag coefficient; fatigue resistance.[23]

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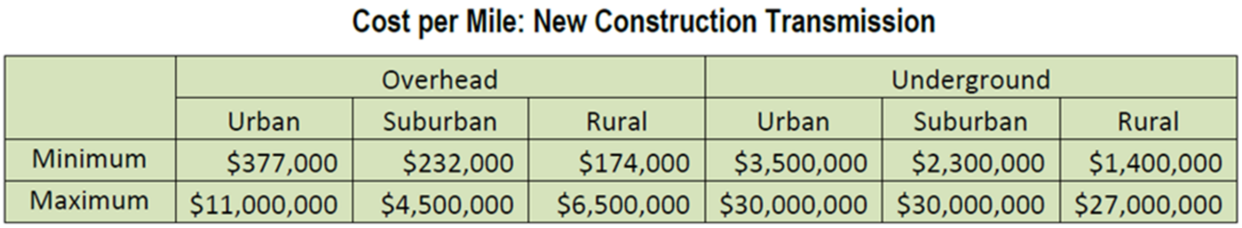
[21] http://www.electrical4u.com/electrical-power-cable, *accessed August 14, 2015*

[22] http://www.eolss.net/sample-chapters/c08/e3-16-03.pdf, *accessed August 14, 2015*

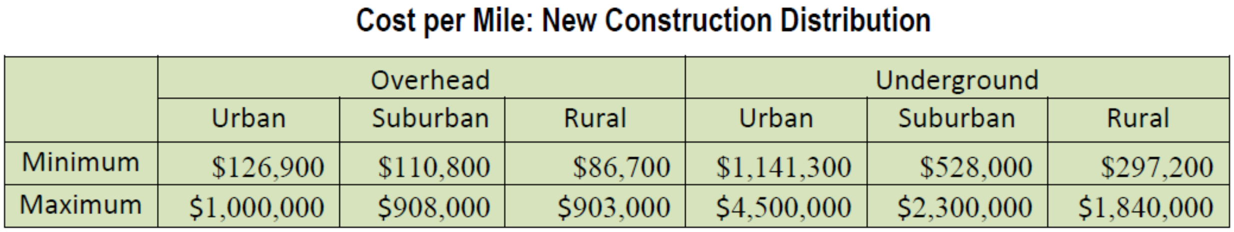
[23] http://www.southwire.com/support/TransmissionConductoraReviewOfTheDesignandSelectionCriteria.htm, *accessed August 14, 2015*

Table 2.8 Cost per Mile for New Transmission and Distribution Construction[24, 25]



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

Figure 2.5 shows the percentages of the elements which are included in the total cost for transmission lines. Material costs and civil costs and are the most expensive elements.

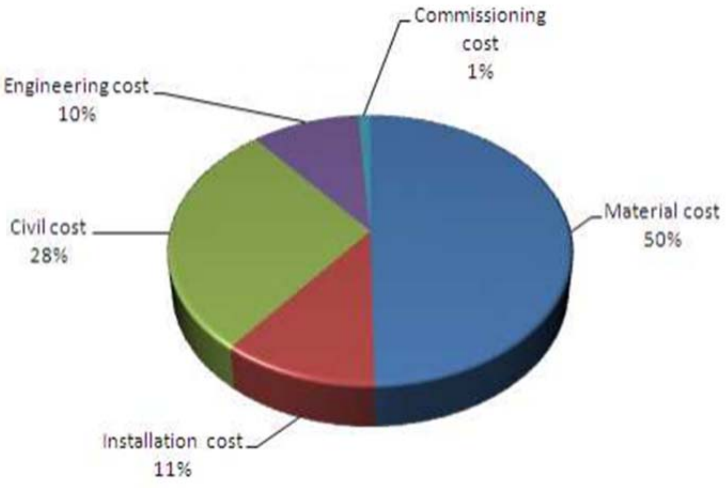


Figure 2.5 Estimated elements of the total cost for 8 km (72.5 kV) transmission line[26]

Utilities and large industrial facilities have extensive systems of cables. Many of these cables are aging and failures are becoming common. A list of failure causes are summarized in Figure 2.6.

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[24] Hall, K. L. "An Updated Study on the Undergrounding of Overhead Power Lines." Hall Energy Consulting Inc., 2012. http://www.eei.org/issuesandpolicy/electricreliability/undergrounding/Documents/UndergroundReport.pdf*, accessed March 16, 2015*

[25] Voltage rating for transmission line is usually larger than 69 kV, distribution line smaller than 69 kV. Alison Silverstein, Transmission 101, NCEP Transmission Technologies Workshop, April 2011. http://www.naruc.org/grants/Documents/Silverstein%20NCEP%20T-101%200420111.pdf.

[26] Juho Yli-Hannuksela, The Transmission Line Cost Calculation, Vaasan Ammattikorkeakoulu University Of Applied Sciences, 2011

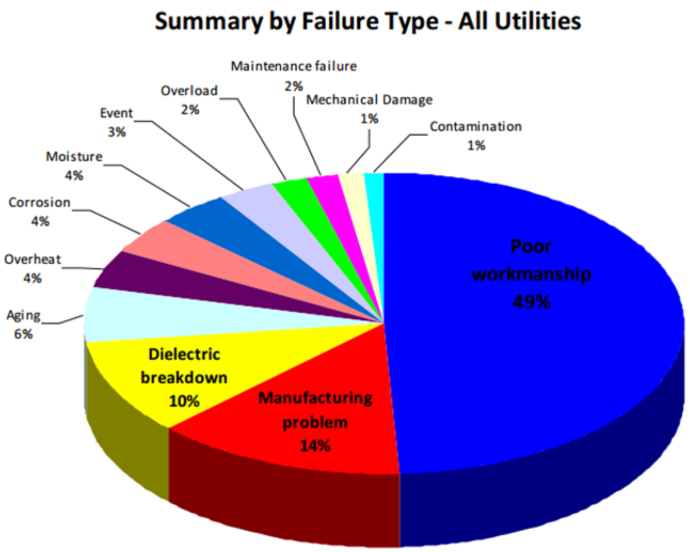

Figure 2.6 Cable Fault Types[27]

CHALLENGES

Table 2.9 Challenges of Cable and Conductors

Cable Failures. Many of these cable systems are aging and failures are becoming common. Diagnostics and installation techniques will improve the operational and maintenance characteristics of current and future cable systems.
Siting and permitting. Difficulties obtaining new rights-of-way or expanding capacity in existing rights-of-way.
Cost. Underground systems have about one-third the failures of overhead systems, but locating and repairing problems can take twice as long. The main impediment for undergrounding lines is cost.
Current Density. For superconducting wire, performance improvements are needed to lower costs and enable more widespread deployment. Cable manufacturers are currently using wire carrying close to 90 Amps/cm widths. Higher capacity wire will decrease the amount of wire required.[28]
Resistive Heating. While carrying high currents, resistive heating will increase operating temperatures leading to sagging. Excessive conductor sagging can result in safety hazards and increase the risk of power failures if the line contacts another object.
Power Loss. Moving more power longer distances with AC overhead transmission lines requires the use of higher voltage lines. Higher electrical losses, as well as reduced power transmission capacity occur as distance from AC line increases.

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[27] http://www.neetrac.gatech.edu/publications/ICC_Fall_2010_ICC_education_session.pdf, *accessed August 14, 2015*

[28] http://www.suptech.com/Cables_Oct_10.pdf

PROTECTION DEVICES AND OTHER SUBSTATION COMPONENTS

System devices such as circuit breakers, isolators, surge arresters, fault current limiters, protective relays, and lightning arrestors help protect critical substation and electric power equipment.

Circuit breakers are necessary at every switching point in a substation. A circuit breaker is an automatically-operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. Its basic function is to detect a fault condition and, by interrupting continuity, to immediately discontinue electrical flow. Isolators are used in addition to circuit breakers and provided on each side of every circuit breaker. It is a mechanical switch that isolates the faulty section or the section of a conductor or a part of a circuit of substation meant for repair from a healthy section in order to avoid occurrence of more severe faults.[29]

Surge arresters discharge the over voltages that can occur due to lightning strikes and switching surges. Substation equipment such as transformers and circuit breakers are typically outdoors and experience many physical stresses. Surge arresters are placed strategically to protect expensive assets.

Current limiting reactors are a well-known fault current limiting technology which is more economical compared to many other short circuit reduction methods. A large number of short-circuit limiting reactors are currently installed in power grids. According to some estimates, there are as many as 44,000 installed worldwide. Under normal operation, a current limiting reactor will always have resistance, which typically causes a power loss of 25 kilowatts. Researchers are attempting to reduce these losses by 50% or more through the use of superconducting fault current limiters (SFCLs). SFCLs have significantly less losses during normal operation. SFCLs use superconducting wire that is cooled to liquid nitrogen temperature using cryogenics systems. However, these cryogenics systems require energy for cooling purposes. On a rough estimate, the power loss of an SFCL can be assumed to total about 50% of the energy consumed by a comparable short-circuit limiting reactor.[30] In addition to SFCLs, the Electric Power Research Institute has conducted research and development on power electronics based fault current limiters.[31]

COMPONENT ANALYSIS

Circuit breakers are the switching and current interrupting device. Basically a circuit breaker comprises a set of fixed and movable contacts. The contacts can be separated by means of an operating mechanism. The separation of current carrying contacts produces an arc. The arc is extinguished by a suitable medium such as dielectric oil, air, vacuum, and SF6 Gas.[32] Cost of circuit breakers varies by types and ratings. A vacuum circuit breaker costs from $15,549 to $38,144 each[33], an oil circuit breaker costs from $28,982 to $83,236 each[34], and a gas SF6 circuit breaker costs from $33,835 to $88,256 each.[35] Table 2.10 below shows the material and labor cost breakdown of a 14.4 kV, 500 MVA oil circuit breaker.

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[29] http://www.edgefx.in/electrical-engineering-substation-components-and-their-workings/

[30] http://www.siemens.com/press/pool/de/pressemitteilungen/2014/corporate/factsheet-supraleiter_e.pdf, *accessed August 14, 2015*

[31] http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001021916, *accessed October 14, 2015*

[32] http://programmablelogiccontrol.blogspot.com/2011/11/study-of-protective-devices-and.html, *accessed August 14, 2015*

[33] http://www.allcostdata.info/browse.html/169163599/Vacuum-circuit-breaker, *accessed August 14, 2015*

[34] http://www.allcostdata.info/browse.html/169160999, *accessed August 14, 2015*

Table 2.10 Cost breakdown of a 14.4 kV, 500 MVA oil circuit breaker.[36]

Item	Rate ($/EA)
Material	27,234
Labor	1,747
Total	**28,982**

SFCLs have the potential as a cost-effective modular solution for protecting transformers, switchgear, and other components against excessive overloads in case of grid failures or circuit feedbacks. The estimated cost breakdown of a 40 MVA SFCL can be found in Figure 2.7. The superconducting material comprises the major cost component for the device.

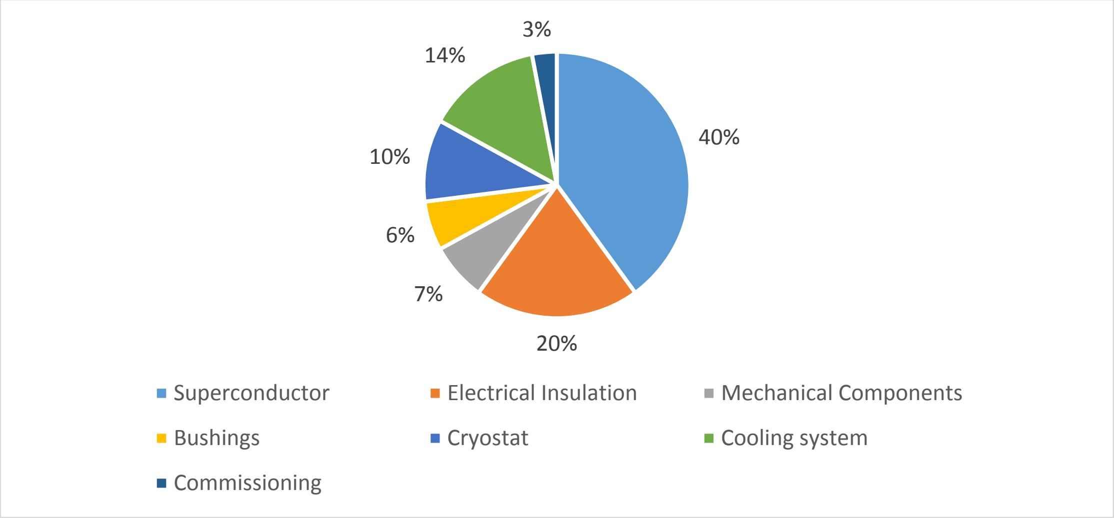

Figure 2.7 Major Cost Components of a 40 MVA SFCL.[37]

CHALLENGES

Table 2.11 Challenges of Protection Devices

Surge Arrestor Costs. Typical station class surge arrestors will need to be built with significant overvoltage margins, which increases cost.[38]
Response Speed. Understanding of arc physics would enable faster time to detect faults and fault locations. Switches made from mechanical and solid state devices need to provide faster interruption capabilities.

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[35] http://www.allcostdata.info/browse.html/169163999/Gas-SF6-circuit-breaker, *accessed August 14, 2015*

[36] http://www.allcostdata.info/detail.html/169161000/Swyd-substa-oil-circuit-breaker,-14.4-KV,-500-MVA, *accessed August 14, 2015*

[37] Economy and Efficiency of Superconducting Systems, Mathias Noe, Karlsruher Institut für Technologie, 6-7 March 2012

[38] http://www.hubbellpowersystems.com/literature/arresters/gen/EU1489WB.pdf, *accessed August 14, 2015*

SFCL Cost. Superconducting wire is expensive. Superconducting fault current limiters require reliable insulation within cryogenic systems that add to the cost and complexity to the system.

Immature DC Circuit Breaker. DC circuit breaker needs to clear the fault current very rapidly, identify the faulted section and reduce long-distance communication time delay.[39]

Reliability. Protection devices need to handle repeated faults that may occur in a short period of time.

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[39] http://www.think-grid.org/dc-networks-and-challenges-protection, *accessed August 14, 2015*

3. MATERIAL INNOVATIONS FOR NEXT GENERATION T&D GRID COMPONENTS

As the electric power system evolves to enable a more resilient and clean energy future, R&D will be needed to understand the physical impact these changes have on vital grid components, identify new technical requirements, and encourage adoption of new technologies and approaches. In particular, applied R&D in advanced materials has the potential to improve the fundamental properties and capabilities of hardware for grid applications and support grid modernization efforts.

This section intends to provide an initial overview to the materials under consideration to improve the capabilities of grid components. While not comprehensive, the intent is to provide non-experts in materials a better understanding of the range and properties of materials under consideration. The following six functional groups of materials are discussed in this section:

1) Active power conversion materials (e.g., semiconductors);
2) Passive power conversion materials (e.g., magnetics);
3) Electrical insulation materials;
4) Electrical conduction materials;
5) Structural support and protection materials;
6) Thermal management materials.

ACTIVE POWER CONVERSION MATERIALS (E.G., SEMICONDUCTORS)

Enable power control, conversion, switching, etc.

MATERIAL CONSIDERATIONS AND RELEVANT PROPERTIES

- Wide bandgap materials in various stages of development are critical to power conversion in electric grid components. These materials include silicon carbide (SiC), gallium nitride (GaN), diamond, aluminum nitride (AlN), zinc oxide (ZnO), and gallium (III) oxide (Ga_2O_3).
- Key material development challenges include developing cost effective wafer and epitaxial layer production and developing new and improved dielectric materials (for junction edge terminations of high voltage power semiconductor devices based on SiC, AlN, diamond).
- Desired operating properties include high voltage, high current, high frequency, high operating temperature, and reduced cooling requirements.
- **Key material properties**: Bandgap energy (eV), critical electric field (V/cm), electron mobility (cm/V·s), breakdown voltage (V), thermal conductivity W/(cm·K), saturation velocity (cm/s), dielectric constant.

WIDE BANDGAP MATERIALS: GALLIUM NITRIDE AND SILICON CARBIDE[40, 41, 42]

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[40] Singh, R. (2006). Reliability and performance limitations in SiC power devices. Microelectronics Reliability, 46, 713–730. doi:10.1016/j.microre1.2005.10.013; Millan, J., Godignon, P., Perpina, X., Perez-Tomas, A., & Rebollo, J. (2014). A Survey of Wide Bandgap Power Semiconductor Devices. IEEE TRANSACTIONS ON POWER ELECTRONICS, 29(5), 2155–2163.; JCN Newswire. (2014). SDK Increases Capacity to Produce 6" SiC Epi-Wafers for Power Devices. Sys-con Media. http://www.sys-con.com/node/3192617.

[41] H. Nie, Q. Diduck, B. Alvarez, A. P. Edwards, B. M. Kayes, M. Zhang, G. Ye, T. Prunty, D. Bour, and I. C. Kizilyalli, “1.5-kV and 2.2-mΩ-cm^2 Vertical GaN Transistors on Bulk-GaN Substrates,” IEEE Electron Device Letters, vol. 35, no. 9, pp. 939-941, Sept. 2014; P. Kruszewski, J. Jasinski,

- **Silicon Carbide (SiC)**: R&D is needed to help address MOS interface quality issues, low channel mobility, elimination of screw dislocations. For example, Cree has devised a combination SiC n-IGBT device with a 27 kV blocking voltage and unipolar SiC FETs with blocking voltages up to 15 kV with 30X reduction in switching losses compared to 6.5 kV silicon IGBTs.
- **Gallium Nitride (GaN)**: While not as well-developed as SiC for grid scale power levels with voltages >1 kV, GaN based devices show promise for these high voltages. A primary challenge is achieving high quality substrate material for bulk GaN devices. Research towards improving material quality and scalability is essential. Possible applicable devices include CAVET, vertical JFET, vertical MOSFET, and very high voltage (10 kV) diodes.

WIDE BANDGAP MATERIALS: DIAMOND, ZnO, AlN, GA_2O_3[43]

- **Diamond** is one of the most promising members of the WBG family because of its high thermal conductivity. Its electrical properties are also attractive and allow for high power density (based on high critical electric field and high carrier mobility).
    - R&D challenges include substrate availability and poor understanding of growth windows. Single crystalline diamond is slowly becoming available and has gained popularity among RF application as a heat sink for GaN.[44]
    - Possible applicable devices include bipolar transistors, FETs (hole and electron channel), IGBT, p-i-n diodes, and p-n diodes.
- **ZnO and AlN** are being considered in academia and industry at various research stages for very high voltage (grid level) semiconductors (e.g., funding in the ARPA-E Switches program). Sustained research is still needed in the next 5-10 years to advance developments to market.
- **Ga_2O_3** is gaining research interest due to its wide bandgap and cost. Possible applicable devices include MISFET or diodes.
    - While the thermal conductivity of Ga_2O_3 is presently not very promising for a power electronic devices, there can be several solutions like thinning and bonding wafers to thermally conductive substrates. Another challenge is developing suitable p-type dopants.

DEVELOPMENT CHALLENGES

NEW AND IMPROVED DIELECTRIC MATERIALS

T. Sochacki, M. Bockowski, R. Jachymek, P. Prystawko, M. Zajac, R. Kucharski, M. Leszczynski, “Vertical Schottky Diodes Grown on Low-Dislocation Density Bulk GaN Substrate,” Int. Workshop Nitride Semiconductor, 2014; http://www.semiconductor-today.com/news_items/2015/may/toyodagosei_060515.shtml. *accessed August 14, 2015*

[42] DOE Advanced Manufacturing Office, Wide Bandgap Semiconductors: Pursuing the Promise, http://energy.gov/sites/prod/files/2013/12/f5/wide_bandgap_semiconductors_factsheet.pdf, *accessed August 14, 2015*

[43] Masataka Higashiwaki’s work; http://www.compoundsemiconductor.net/article/89570-gallium-oxide-trumps-traditional-wide-bandgap-semiconductors.html, *accessed August 14, 2015*

[44] F.A.M. Koeck et al., “Thermionic electron emission from low work-function phosphorus doped diamond films”, *Diamond Relat. Mater.*, vol. 18, no. 5-8, pp. 789-791, May-Aug. 2009; A.G. Redfield, "Electronic Hall Effect in Diamond", *Phys. Rev.*, vol. 94, no. 3, pp. 526-527, May 1954; L. Reggiani et al., "Hole-drift velocity in natural diamond", *Phys. Rev. B*, vol. 23, no. 6,pp. 3050-3067, Mar. 1981; S. Koizumi et al., "Phosphorus-doped chemical vapor deposition of diamond", *Diamond Relat. Mater.*, vol. 9, no. 3-6, pp. 935-940, Apr.-May 2000; K. Oyama et al., "High performance of diamond p+-i-n+ junction diode fabricated using heavily doped p+ and n+ layers", *Appl. Phys. Lett.*, vol. 94, no. 15, pp. 152109-1-152109-2, Apr. 2009; R. Kalish et al.,"The search for donors in diamond", *Diamond Relat. Mater.*, vol. 10, no. 9-10, pp. 1749-1755, Sept.- Oct. 2001.; S. Yamasaki et al., "Doping and interface of homoepitaxial diamond for electronic applications", MRS Bull., vol. 39, no. 6, pp. 499-503, Jun. 2014.; S. Koizumi et al. , "Growth and characterization of phosphorous doped {111} homoepitaxial diamond thin films", Appl. Phys. Lett., vol. 71, no. 8, pp. 1065-1067, Aug. 1997.

- New and improved dielectric materials are needed for the junction edge terminations of 20 kV+ SiC/AlN/diamond power semiconductors. The edge region of a vertical semiconductor device, used to support blocking voltage, needs to be reduced in order to reduce the cost of WBG materials.[45]
- Packaging for high voltage WBG devices experience dielectric considerations not typically involved for silicon devices. When packaging semiconductors in power modules, protecting the dies against external factors such as humidity and contaminants need to be considered. Higher voltage ratings of require insulators with extended breakdown capability and lower creepage. Higher dv/dt gradients are also common for WBG semiconductors, and introduce additional challenges on the materials being used.

COST EFFECTIVE WAFER AND EPITAXIAL LAYER PRODUCTION

- Very high voltage power semiconductors (20 kV+) may play a transformational role in the grid of the future. To bring these semiconductors closer to market, more research is needed to promote cost effective wafer and epitaxial layer production (4”, 6” and 8”).

PASSIVE POWER CONVERSION MATERIALS (E.G., MAGNETICS)

Includes soft and hard magnetic materials critical to energy conversion applications

MATERIAL CONSIDERATIONS AND RELEVANT PROPERTIES[46]

- Magnetic steel
- Soft ferrite
- Soft Iron
- Silicon steel laminates
- High performance soft magnetics materials
- Dual phase magnetic materials for electric machine laminates
- Higher performance permanent magnets
- Nanostructured soft magnetic materials for high frequency inductors and transformers
- **Desired operating properties**: high frequency, high saturation, lightweight, low loss, high resistivity, high permeability, low or no rare earth material content, high Curie temperature, low coercivity.

HIGH PERFORMANCE SOFT MAGNETICS MATERIALS

- Next generation, novel high performance soft magnetics materials for transformer and inductor cores used in WBG-based power conversion systems.

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[45] M. Wolborski (2006), “Characterization of Dielectric Layers for Passivation of 4H-SiC Devices”, Ph.D. thesis, KTH Sweden; M. Usman, C. Henkel, and A. Hall´en (2013). HfO2/Al2O3 Bilayered High-*k* Dielectric for Passivation and Gate Insulator in 4H-SiC Devices, *ECS Journal of Solid State Science and Technology*, **2** (8) N3087-N3091

[46] http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6971577; http://link.springer.com/chapter/10.1007%2F978-3-662-44529-7_4#page-1, *accessed October 16, 2015*

DUAL-PHASE MAGNETIC MATERIALS FOR ELECTRIC MACHINE LAMINATES[47]

- Dual phase magnetic materials allow local heat treatment of a lithographically patterned laminate to "switch-off" the magnetization of selected areas while the mechanical properties remained "switched-on", enabling novel high-efficiency synchronous reluctance machine topologies.

NANOSTRUCTURED SOFT MAGNETIC MATERIALS FOR HIGH FREQUENCY INDUCTORS AND TRANSFORMERS[48]

- Higher performance soft magnetic components are critical to enabling the use of wide bandgap semiconductors (with high switching frequencies) in high power electronics. Optimal soft magnetic component materials combine the low power loss of high frequency oxide ferrites with the high magnetization of metallic components such as iron and permalloy, operating at kHz to MHz frequencies and kW to MW power ratings. Advanced manufacturing methods are required to engineer multiphase nanogranular composites in both planar and bulk form factors. High rate physical vapor deposition is one scalable manufacturing method that could achieve these goals, however the need to precisely control the fabrication of the nanostructures is a key challenge to be overcome.

ELECTRICAL INSULATION MATERIALS

Dielectrics and insulating solids and fluids (including gases)

MATERIAL CONSIDERATIONS AND RELEVANT PROPERTIES

- Polymers (e.g. XLPE), ceramics (e.g., alumina, steatite)
- Insulating fluids (e.g., transformer oil, liquid nitrogen for superconductors)
- Insulating gases (e.g., SF_6, air, halogens)
- Nanofluids (NFs)
- Compatible insulators
- High temperature and high voltage insulation
- Replacement for SF_6 insulation
- Low cost HVDC cable insulation
- Stress grading materials for high voltage apparatus
- **Desired operating properties:** High voltage/fields, high electrical resistance, operation at elevated, temperatures, high dielectric constant/permittivity or high electric susceptibility, high

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[47] L.C. Dial, R. DiDomizio, F. Johnson, "Dual Phase Magnetic Material Component and Method of Forming, U.S. Patent Application 20150115749/A1, filed October 31, 2013.

[48] M.A. Willard and M. Daniil, "Nanostructured Soft Magnetic Alloys Two Decades of Progress," Handbook of Magnetic Materials, Vol. 21, 2013, pp. 173-342.; B. Balamurugan, D.J. Sellmyer, G.C. Hadjipanayis, R. Skomski, "Prospects for nanoparticle-based permanent magnets," Scripta Mat., Vol. 67, 2012, pp. 542-547; F. Johnson, R.E. Colborn, J.S. Marte, P.J. Bonitatibus, B.I.I. Kandapallil, M. Haouaoui, C. Chen, "Nanocomposite permanent magnets and methods of making the same," U.S. Patent Application 20140002220, filed June 29th, 2012.; O. Gutfleisch, M.A. Willard, E. Brück, C.H. Chen, C.H., S.G. Sankar, J.P.Liu, "Magnetic materials and devices for the 21st century: Stronger, lighter, and more energy efficient," Advanced Materials, Vol. 23, 2011, pp. 821-842; .; J.M.D. Coey, "Hard magnetic materials: a perspective," Vol. 47, 2011, pp. 4671-4681.; L.E. Iorio, P.R. Subramanian, "Magnetic layer with nanodispersoids having a bimodal distribution," U.S. Patent 7,989,095, filed December 28th, 2004. ; http://arpa-e.energy.gov/?q=slick-sheet-project/additive-manufacturing-electric-vehicle-motors, *accessed October 16, 2015*; http://arpa-e.energy.gov/?q=arpa-e-programs/react, *accessed October 16, 2015*

breakdown voltage, high reliability (long mean time before failure), thermal management of multilayer devices and control of self-healing.

VARIOUS PROPERTIES TO CONSIDER

- Controlled heterogeneity in ceramic insulators to achieve a more reliable operation under harsh conditions (i.e. high temperature, high current, high fields).
- Understanding the role of defect migration under high temperatures and high fields will be necessary to prevent premature failures.
- Developing tools to analyze heat and ionic defect transport to diagnose failure in new designs.[49]

NANOFLUIDS (NFS)

- The addition of nanoparticles (e.g., titania, Cu) to transformer (e.g., mineral and perhaps ester) oils has been shown to increase dielectric breakdown strength and thermal conductivity.[50]

INSULATORS FOR HTS APPLICATIONS

- Research and development is needed to identify and optimize insulator materials for HTS applications.

HIGH TEMPERATURE AND HIGH VOLTAGE INSULATION[51]

- Insulation systems designed for operation under 50 or 60 Hz voltage can experience accelerated insulation degradation when exposed to the rapid rise of repetitive impulse voltages.
- Proper insulation design can enable an MV motor insulation system that provides the same or better run life at fundamental frequencies of 500 Hz or higher as at 60 Hz. In addition, monolithic nanocomposite insulation systems can replace traditional mica tape systems for high temperature applications. Such insulation systems can be used for power generators, high voltage bushings, and high voltage insulators.

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[49] N. Raengthon, T. Sebastian, D. Cumming, I. M. Reaney, and D. P. Cann, "BaTiO3-Bi(Zn1/2Ti1/2)O3-BiScO3Ceramics for High-Temperature Capacitor Applications," Journal of the American Ceramic Society, 95[11] 3554-61 (2012); A. Zeb, Y. Bai, T. Button, and S. J. Milne "Temperature-Stable Relative Permittivity from −70°C to 500°C in (Ba0.8Ca0.2)TiO3-Bi(Mg0.5Ti0.5)O3-NaNbO3Ceramics," Journal of the American Ceramic Society, 97[8] 2479-83 (2014).; D. P. Shay, N. J. Podraza, N. J. Donnelly, and C. A. Randall, "High Energy Density, High Temperature Capacitors Utilizing Mn-Doped 0.8CaTiO3-0.2CaHfO3 Ceramics," Journal of the American Ceramic Society, 95[4] 1348-55 (2012).; http://www.presidiocomponents.com/catalog/HighTempCeramicCapsRevM-May2015.pdf; http://www.kemet.com/Lists/TechnicalArticles/Attachments/39/2013-03%20CARTS%20-%20High%20Temp%20Ceramic%20Capacitors%20for%20Deep%20Well%20Applications.pdf, *accessed October 16, 2015*

[50] TiO_2 NFs: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6215079; http://scitation.aip.org/content/aip/journal/jap/110/10/10.1063/1.3660783; http://link.springer.com/article/10.1007%2Fs11051-009-9658-2; http://www.sciencedirect.com/science/article/pii/S1364032110004041, *accessed October 16, 2015*

[51] W. Yin, F. Tao, J. Zhao, G. Chen, D. Schweickart, “Failure mechanisms of polyimide and perfluoroalkoxy films under high frequency pulses,” IEEE IPMHVC Conference, 2010.; F. Tao, W. Yin, D. Schweickart, “Development of a High Voltage, High Frequency, Fast dV/dt Tester for the Study of Failure Mechanisms in Dielectric Materials,” IEEE IPMHVC Conference, 2010.; W. Yin, P. Irwin, D. Schweickart, “Dielectric Breakdown of Polymeric Insulations Aged at High Temperatures,”IEEE IPMHVC Conference, 2008.; W. Yin, D. Schweickart, “Dielectric Breakdown of Polymeric Insulation Films Under AC, DC and Pulsed Voltages,” IEEE Electrical Insulation Conference, 2009.; D. Manns et al., “The Design and Testing of Insulation Systems for Large Rotating Machines Powered by Adjustable Speed Drives,” 11th INSUCON International Electrical Insulation Conference, Birmingham, UK, 26-28 May 2009.; W. Yin, K. W. Flanagan, R. C. McTigue, M. Rodda, S. Kniajanski, “Corona-resistant wire enamel compositions and conductors insulated there with,” US Patent 8784993, 2014; P. Irwin, D.Q. Tan, X. Fang, N. Silvi, Y. Cao, W. Yin, “In-situ polymerized nanocomposites,” European Patent Application 2230272 A3.; W. Yin, L. Zhang, L. Durantay, J. F. Grignard, “Electrical insulation system,” US Patent Application 20140353000 A1, 2015

SF_6 INSULATION REPLACEMENT[52]

- Displacing SF_6 insulation from gas insulated (GI) switchgear will abate a major source of greenhouse gas pollution from the power distribution and transmission grid. Recent approaches to SF_6 replacement in electrical equipment have yielded incremental progress. Combining computation and empirical experiment creates the possibility of considering the feasibility of all gasses.

LOW COST HVDC CABLE INSULATION[53]

- DC cables account for up to 70% of the system cost. DC cable insulation must be able to suppress space charge accumulation and control DC resistive grading. Today's extruded DC XLPE cable insulation is modified from AC cable insulation, resulting in both high cost and limited performance because the two types of cables are optimized for different requirements. ARPA-E recently funded a demonstration of a novel nanoclay-EPR DC cable insulation with very low space charge and without needing the costly fabrication process for DC XLPE.
- This insulation is based on a micro-laminated structure rather than high purity. Further formulation optimization and validation of the nanoclay-EPR insulation is needed on full-scale cables. Exploration is also needed into other extrudable micro/nano-laminated insulations with further improved DC resistivity and space charge dissipation than the nanoclay-EPR system.

STRESS GRADING MATERIALS FOR HIGH VOLTAGE APPARATUS[54]

- Reducing maximum stress is important for insulation systems that involve multiple insulation materials, such as HV bushings and GIS. Control of electrical stress is achieved using stress grading materials (SGM) whose conductivity and/or dielectric constant increase with electric field. Today's SGMs are made of nonlinear inorganic fillers randomly distributed in linear organic matrix.
- Innovations that could dramatically increase SGM performance include:
  - Design optimization for SGM morphology, including filler size/shape and matrix connectivity.
  - Control of SGM morphology, combining chemical methods at nanometer-scale and additive manufacturing (e.g., 3D printing) at the micron- to millimeter-scale.
  - Novel SGM with homogeneous morphology instead of two-phase morphology in existing SGMs. Nonlinearity can be achieved by proper engineering of energy level

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[52] Emission Reduction Partnership for Electric Power Systems 2013 Annual Report, United States EPA, April 2014; REGULATION (EU) No 517/2014 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, Official Journal of the European Union, May 2014.; McNulty, Mike, et. al, "SF6 Eqpuiment Maintenance, Repair, and Replacement and Emissions Pograms," U.S. EPA's 2012 Workshop on SF6 Emission Reduction Strategies, April 2012.; LG Chrisophorou, et. al, "Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure SF6," U.S. Government Printing Office, Technical Note 1425, 1997.; J.C. Devins, "Replacement Gases for SF6," IEEE Transactions on Electrical Insulation, Vol. EI-15 No. 2, pp. 81-86, April 1980.; J.C. Devins, et. al, "Electrical apparatus and gaseous dielectric material therefor comprising perfluoroalkylnitrile," US Patent 3048648, 1962.; http://www.alstom.com/Global/OneAlstomPlus/Grid/PDF/Alstom_Spotlight_g3%20April%202015.pdf?epslanguage=en-GB; http://www.think-grid.org/additional-content-search-sf6-replacement; http://www.mena.abb.com/cawp/seitp202/2b2961720afd29e6c1257d3c0026665c.aspx, *accessed October 16, 2015*

[53] DOE FOA DE-FOA-0000473: GREEN ELECTRICITY NETWORK INTEGRATION (GENI); R.N.Hampton, "Some of the considerations for materials operating under high-voltage, direct-current stresses", IEEE Electrical Insulation Magazine, vol 24, no. 1, pp 5-13 (2008); Q. Chen, "Nanoclay-Reinforced Ethylene-Propylene-Rubber for Low Cost HVDC Cabling", final report, ARPA-E project DE-AR0000231

[54] T. Christen et al, " Nonlinear resistive electric field grading", IEEE Electrical Insulation Magazine, Part 1: vol. 26, no. 6, pp 47-59 (2010); Part 2: vol 27, no. 2, pp 18-29 (2011); Y. Tokura et al, " Nonlinear electric transport and switching phenomenon in the mixed-stack charge-transfer crystal tetrathiafulvalene-p- chloranil", vol. 38, no. 3, pp 2215-2219 (1988); Q. Chen, "Subsea DC Connector Study", in " MSDC Electrical System for Deepwater Subsea Process", DOE/RPSEA project 08121-2901-01 final report (2013)

distributions in semi-conductive polymers, creating highly nonlinear rectifying junctions without invoking inorganic fillers.

ELECTRICAL CONDUCTION MATERIALS

Metals and conductors for transmission and distribution of electricity, including interconnections

MATERIAL CONSIDERATIONS AND RELEVANT PROPERTIES

- Copper
- Aluminum (e.g., AAC, ACSR)
- High temperature superconductors
- High temperature solders and fixtures
- Improved electrical contacts
- Advanced metals/conductors with increased conductivity
- High ampacity and lightweight metal/carbon nanotubes hybrid conductor for wires and cables
- **Desired properties**: Low resistance, high reliability, high mechanical strength, low weight, high current density, operate/withstand high temperatures.

IMPROVED ELECTRICAL CONTACTS

- Electrical contacts are found inside switches, relays, circuit breakers in the power grid. Improving these contacts through advanced materials research, such as improving SnO_2 content, will help reduce arc erosion and therefore increase life span of critical switching devices. New manufacturing techniques such as 3D printing can help achieve this goal.

ADVANCED METALS/CONDUCTORS WITH INCREASED CONDUCTIVITY

- Conduction losses are a significant limitation in system efficiency. These losses also generate significant heat, which strongly impacts cooling requirements and overall system cost.
- Advanced metals/conductors with increased conductivity over copper and specific conductivity (conductivity/mass-- aluminum) at economic cost levels are needed for new generation of highly efficient transformers.

INDUSTRIALIZED HIGH TEMPERATURE SUPERCONDUCTORS

- High temperature superconductors need significant industrialization to optimize minimum piece length and uniformity. Improvement in engineering parameters and yield will require a very significant capital investment.

HIGH AMPACITY AND LIGHTWEIGHT METAL/CNT HYBRID CONDUCTOR FOR WIRES AND CABLES[55]

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[55] Subramanian, C., Yamada, T., Kobashi, K., Sehiguchi, A., Futaba, D., Yumura, M., Hata, K., Nature Communications,4:2202, 2013.; Ko, W-Y.,Lin, K-J., Journal of Nanomaterials, Volume 2013, Article ID 505292, 16 pages, 2013. doi:10.1155/2013/505292; Gang Qin, Akira Watanabe, Hiroki Tsukamoto, and Tetsu Yonezawa, Japanese Journal of Applied Physics 53, 096501 (2014); Lekawa-Raus , J. Patmore , L. Kurzepa , J. Bulmer , andK. Koziol, Adv. Funct. Mater. 2014, 24, 3661–3682; S. Harvey, Proceedings of the 61st IWCS Conference, 558-562; N. Behabtu et al.Science 339, 182 (2013); Y. Zhao, J. Wei, R.Vajtai, P. Ajayan & E. V. Barrera, SCIENTIFIC REPORTS | 1 : 83 | DOI: 10.1038/srep00083; Phase 1 Final Presentation: Ultra-High Conductivity Umbilicals: Polymer Nanotube Umbilicals, 2013.
STTR Phase I: Conversion of Enhanced Copper Foils to Wire Forms, 2013. Available at: https://sbirsource.com/sbir/awards/153833-sttr-phase-i-conversion-of-enhanced-copper-foils-to-wire-forms, *accessed October 16, 2015*

- Increasing power demand has led to the need to develop conductors that are able to transmit more power in a smaller footprint (e.g., transformers for substations) and lighter weight (e.g., overhead cable) than copper and aluminum. Single CNT fiber has lower resistivity, higher mechanical strength, and weighs at least 4 times lighter than Cu. However, due to high porosity between CNT fibers and fiber joints, CNT wires made of CNT fibers currently have resistivities that are too high for them to serve as a full replacement for metals.

STRUCTURAL SUPPORT AND PROTECTION MATERIALS

Applications include transformer housing, power electronics packaging, transmission towers, cable structural support, etc.

MATERIAL CONSIDERATIONS AND RELEVANT PROPERTIES

- Steel
- Alloys
- Aluminum-Steel hybrids
- Composites
- Ceramics
- Synthetic packaging 3D woven composites
- Fiber reinforced plastic foams
- Nano stitched functional composites
- **Desired properties**: Corrosion resistance, high strength, lightweight, self-Healing, flexibility in joining, dissimilar materials, reliability – thermal cycling, fatigue, High current, high switching, low inductance (PE packaging), ability for high shielding from EMP

3D WOVEN COMPOSITES

- 3D woven composites have exceptional strength-to-weight ratios, and can have properties such as integrated sensing, self-healing, electrical conduction, etc. [56]

FIBER REINFORCES PLASTIC FOAMS

- Fiber reinforced plastic foams (e.g., Airex) with enhanced strength-to-weight could enable lighter and more flexible power electronic systems.[57]

NANOSTITCHED FUNCTIONAL COMPOSITE[58]

- Next generation fiber reinforced polymer composites (FRPC) can be stronger, tougher, and multifunctional. Based on Nanostitch™ technology, these smart structures of low-cost, high-volume vertically-aligned carbon nanotubes (VACNTs) are produced using an innovative continuous manufacturing process that can be tuned for electrical protection and increased thermal conductivity.

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[56] Anthony Coppola et al., Tensile properties and damage evolution in vascular 3D woven glass/epoxy composites. Available at: http://www.sciencedirect.com/science/article/pii/S1359835X13003436, *accessed October 16, 2015*

[57] AIREX® Structural foam cores. Available at: http://www.3accorematerials.com/products/airex/airexregpxw.html, *accessed October 16, 2015*

[58] Garcia, E.J., Wardle, B.L., Hart, J., and A. Slocum, "Joining Prepreg Composite Interfaces with Aligned Carbon Nanotubes" Composites Part A, Vol. 39, Issue 6, June 2008, pp. 1065-1070.

- Such materials can have significant impact on reducing the size and weight of enclosures/packaging as well as support structures of various apparatus.

THERMAL MANAGEMENT MATERIALS

Thermal management for grid hardware components such as transformers, power electronics, etc.

MATERIAL CONSIDERATIONS AND RELEVANT PROPERTIES

- Copper
- Aluminum
- Metal matrix composites (MMCs) e.g., Al/SiC
- Polymer matrix composites (PMCs)
- Working fluid
- Phase change materials (PCMs)
- Particle immersed liquids
- Graphene
- Ultra high molecular weight polyethylene (UHMWPE) fibers
- Elastocaloric cooling with shape memory alloys
- More efficient thermoelectrics
- Improved cryogenic design
- Thermally conductive epoxies
- Oscillating polymer heat pipes
- Filled polysialte system
- **Desired properties**: High thermal conductivity, low corrosion, minimized weight, reduced size, ability to recover waste heat, high reliability, high emissivity

PARTICLE IMMERSED LIQUIDS

- Particle immersed liquids can increase the thermal conductivity of the cooling oil in transformers. More research is needed to identify the right particle-oil systems and their impact on other system-level performance criteria.

GRAPHENE

- Graphene (thermal conductivity k>4,000 W/m/K) is a high potential material for cooling. More research is needed to understand how to benefit from the properties of graphene in connection with typical T&D components, including manufacturing methods.[59]

ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE (UHMWPE) FIBERS

- UHMWPE fibers: drawn PE nanofibers exhibit thermal conductivities up to ~100 W/m/K due to good alignment of polymer chains (for reference, bulk PE has k<0.5 W/m/K).[60]

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[59] Alexander A. Balandin et al., *Superior Thermal Conductivity of Single-Layer Graphene*, Nano Letters, 2008. Available at: http://pubs.acs.org/doi/abs/10.1021/nl0731872, *accessed October 16, 2015;* Shanshan Chen et al., Thermal conductivity of isotopically modified graphene, 2012. Available at: http://www.nature.com/nmat/journal/v11/n3/abs/nmat3207.html, *accessed October 16, 2015*

[60] Sheng Shen et al., *Polyethylene nanofibres with very high thermal conductivities*, 2010. Available at: http://www.nature.com/nnano/journal/v5/n4/abs/nnano.2010.27.html, *accessed October 16, 2015*

MULTIFERROIC MATERIALS

- Magnetocaloric effect (MCE) cooling at room temperature can also be explored, with more research into identifying and optimizing new MCE materials for grid hardware thermal management.
- Elastocaloric cooling with shape memory alloys can be an efficient cooling technology, but more research is needed to fully understand the application space and performance criteria.[61]

MORE EFFICIENT THERMOELECTRICS

- More efficient thermoelectrics can be used for waste heat recovery in power electronic and grid related applications. If more heat losses were captured and converted to electricity, this could enable powering of a wide range of accessories (e.g., gate drives in power electronics, or sensors and their communication in power transformers).[62]

IMPROVED CRYOGENIC DESIGN

- With respect to HTS applications, many failures can be attributed to the lack of known cryogenic design.

THERMALLY CONDUCTIVE EPOXIES

- Epoxies and varnishes are used in electrical/electronic equipment for structural integrity and thermal management. State-of-the-art molding compounds commonly used today have thermal conductivities less than 0.3 W/m-K. Improved epoxy thermal conductivity leads to improved thermal management and increased insulation life. The same cooling architecture and insulation system can be employed for running equipment at higher current or power densities without affecting operating life.
- For effective heat removal and increased power density, potting materials with improved thermal properties are desired. Recently, magnesium oxide (MgO) was demonstrated as a useful epoxy additive; MgO-filled epoxy was demonstrated to have a high dielectric strength, at the same time being relatively soft.[63] Other possible candidates include Aluminum Nitride (AlN) and hexagonal Boron Nitride (h-BN).[64]

IMPROVED PHASE CHANGE MATERIALS (PCMS)

- Phase change materials (PCMs) are used for thermal energy storage (TES) and absorption. With PCMs, generated thermal energy is absorbed to change the phase from solid-to-liquid (or solid-to-solid); and the phase change is reversible (PCMs resolidify and release the absorbed heat, when the operating temperature is lowered below the melting point). TES is increasingly used in industrial applications to reduce temperature cycling and overall temperature rise without under-powering the system.

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[61] Jun Cui et al., *Demonstration of high efficiency elastocaloric cooling with large DT using NiTi wires*, Applied Physics Letters, 2012. Available at: http://www.mse.umd.edu/sites/default/files/documents/faculty/takechui/151.pdf, *accessed October 16, 2015*

[62] K. Smith and M. Thorton, *Feasibility of Thermoelectrics for Waste Heat Recovery in Conventional Vehicles*, 2009, http://www.nrel.gov/docs/fy09osti/44247.pdf, *accessed October 16, 2015*; Ashwin Date et al., *Progress of thermoelectric power generation systems: Prospect for small to medium scale power generation*, 2014. Available at: http://www.sciencedirect.com/science/article/pii/S1364032114001038, *accessed October 16, 2015*

[63] Wereszczak, A.A., Morrissey, T.G., Volante, C.N., Farris, P.J., Groele, R.J., Wiles, R.H., and Hsin Wang, “Thermally Conductive MgO-filled Epoxy Molding Compounds,” IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 3(12), pp. 1994-2005, 2013.

[64] Thermally Conductive Organic Dielectrics for Power Electronics and Electric Motors, 2013 Vehicle Technologies Annual Merit Review, 2013. Available at: http://energy.gov/sites/prod/files/2014/03/f13/pm037_wereszczak_2013_o.pdf, *accessed October 16, 2015*

- Most PCMs, including salts and paraffin, possess poor thermal conductivity (<0.25 W/m-K) and require an internal thermal enhancement structure such as fins or fillers, to enable the heat storage with a minimal rise in temperature.

OSCILLATING POLYMER HEAT PIPES[65]

- An oscillating heat pipe (OHP) is a special type of heat pipe without any internal wick; the driving force for motion/heat transfer is the slug/plug motion of the vapor and liquid phases in the serpentine channels, generated via evaporation and condensation.
- Polymer-based oscillating heat pipes eliminate the use of metals (e.g., copper), and utilize extremely thin Kapton or PEEK as casing material for reducing the thermal conduction resistance. This makes these heat pipes electrically insulating and potentially flexible, at the same time reducing the overall weight, compared to conventional metallic heat pipes.

FILLED POLYSIALTE SYSTEM[66]

- Polysialate and geopolymer composites are interesting due to their inherent high temperature resistance, low density and ease of manufacturing. Polysialate composites can exhibit stable thermal properties up to 1000 °C which may open up high temperature hardware components. With additive fillers in the composites, electrical and thermal conductivity can be tuned.

MATERIAL CONSIDERATIONS AND RELEVANT PROPERTIES

- Oxides for chemical sensing (oxides, oxide nanocomposites, porous oxides)
- Polymers for chemical sensing
- Magnetic materials for field and current sensing (inductive materials, magnetostrictive materials, GMR materials)
- Semiconductors for magnetic field and current sensing (hall sensors)
- Materials for sensing device platforms (packaging, insulation, solders)

OTHER ISSUES

MATERIAL SCALABILITY AND PROCESSING

While lab scale developments of high performance materials are interesting, more effort is needed on the commercialization side of these materials, and modification of manufacturing methods for cost effectiveness of final components.

ADDITIVE MANUFACTURING TECHNOLOGIES[67]

Additive manufacturing technology holds great promise for enhancing the performance of electric power conversion systems. For example, an ARPA-E funded project has explored laser deposition of copper conductors to enable a non-rare-earth containing electric machine. As additive methods mature,

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[65] Ogata, S., Sukegawa, E., Kimura, T., “Performance evaluation of ultra-thin polymer pulsating heat pipes”, Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2014 IEEE Intersociety Conference, Orlando, FL, (DOI: 10.1109/ITHERM.2014.6892325

[66] Browna, M.J., Pottera, K., Fosterb, S., Bathob, T., “Thermal and tensile properties of polysialate composites” Ceramics International, Volume 39, Issue 8, December 2013, Pages 8917–8924.

[67] Additive Manufacturing for Electric Vehicle Motors, United Technologies Research Center (UTRC)
Additive Manufacturing of Optimized Ultra-High Efficiency Electric Machines. Available at: http://arpa-e.energy.gov/?q=slick-sheet-project/additive-manufacturing-electric-vehicle-motors, *accessed October 16, 2015*

this technology is expected to extend to the deposition of other functional materials, including insulation and magnetic materials. Soft magnetic composites (SMCs), an existing technology with conventional processing methods, are a promising candidate for development with additive manufacturing techniques.

SENSING MATERIALS

Sensors are needed to help asset monitoring or improve performance and add examples. Sensing materials play a critical role in acting as the element that transduces changes in a parameter of interest to something a device can measure. For example, various types of oxide thin films or polymeric films for chemical sensing. Similarly, magnetic materials can be used for current and magnetic field sensing. As power electronics converters become more prevalent, a need for monitoring electrical parameters at frequencies approaching the kHz – MHz range instead of just at 60Hz will become increasingly important. Similarly the need to monitor EMI, etc. One tangible example, chemical sensing materials are required for developing real-time sensor solutions for dissolved gas analysis in power transformers and insulation oils for other grid components.