WHITEPAPER

MODERNIZING THE POWER GRID

WITH PEAK HIGH VOLTAGE CAPACITOR FILMS

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EXECUTIVE SUMMARY

79%
SURGE
IN POWER DEMAND

The global power grid is undergoing a transformation driven by surging energy demands and the integration of renewable sources. Increasingly, traditional infrastructures are struggling to keep pace, necessitating grid modernization initiatives that enhance efficiency, scalability, and resilience. This paper explores key challenges facing modern power grid operators and the role of capacitors in addressing these demands. This document also reveals how Peak NanoPlex™ films are enabling next-generation capacitors to support grid stability, efficiency, and longevity.

INTRODUCTION: POWER GRIDS STRAINING TO ADDRESS MOUNTING DEMANDS

GROWING RAPIDLY

The global power grid is experiencing unprecedented growth as industries, consumers, and emerging technologies demand more energy than ever before. Artificial intelligence (AI), electric vehicle (EV) adoption, and the ongoing transition to electricity-powered industrial and residential systems are some of the key drivers of this growing demand. According to projections, there will be a 79% surge in power demand by 2050, necessitating significant infrastructure upgrades and innovation.[1]

UNDER INCREASED STRAIN

The aging grid infrastructure is ill-equipped to handle the increasing energy demands of the modern world. Many power grids were designed decades ago and are now struggling to maintain efficiency and reliability. This has led to increased losses in power transmissions, higher operational costs, and frequent system failures. Without modernization, these penalties will only continue to mount.

[1] Ignition Research, "Fusion Energy Worldwide Demand Report," August 27, 2024, URL: https://ignitionresearch.com/reports-fusion-energy-worldwide-demand-market-report/

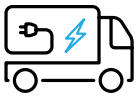
EVOLVING RAPIDLY

The need for a more adaptive, secure, and resilient grid has accelerated advancements in power transmission, distribution, and consumption. Power grids are undergoing rapid evolution as operators seek to accommodate increasing demand and respond to shifting power generation trends. Here are a few of the key changes underway:

Renewable integration. Grid operators continue to contend with the ramifications of an evolving mix of energy sources, including expanding solar and wind generation.

Expansion of energy storage systems. To contend with increasingly large fluctuations in both production and demand, operators need to continue to increase energy storage capacity.

Adoption of smart grid technologies. Technology advances continue to be made in virtually every aspect of grid operations. Smart grid technologies are a critical component of modernizing power systems. These innovations include digital monitoring, automated fault detection, and real-time data analytics, which enable operators to optimize energy flow and improve overall grid efficiency.



Mobility and resilience. As they contend with the heightened risk of devastating cyber attacks and natural disasters, grid operators have grown increasingly reliant on mobile energy production that can safeguard power delivery and enhance overall grid reliability.

ADAPTIVE
SECURE
RESILIENT
GRID

SMART GRID TECHNOLOGIES ARE A CRITICAL COMPONENT OF MODERNIZING POWER SYSTEMS. THESE INNOVATIONS INCLUDE DIGITAL MONITORING, AUTOMATED FAULT DETECTION, AND REAL-TIME DATA ANALYTICS, WHICH ENABLE OPERATORS TO OPTIMIZE ENERGY FLOW AND IMPROVE OVERALL GRID EFFICIENCY.

GRID MODERNIZATION

EVOLVING RAPIDLY

Grid modernization refers to the enhancement and replacement of the components that make up the power grid. There are two key objectives:

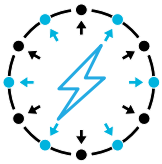
- First, replacing aging infrastructure, which can present an increasingly critical liability as the demands and complexities of grids continue to grow.
- Second, through modernization, grid operators seek to accelerate the adoption and optimization of new technologies.

Grid modernization is a comprehensive initiative that involves upgrading outdated electrical infrastructure, incorporating digital monitoring and control mechanisms, and deploying advanced materials to improve system efficiency and resilience. These efforts ensure that modern grids can handle increased loads, integrate intermittent renewable energy sources, and minimize transmission losses.

Through modernization, grid operators can gain significant benefits, including improving efficiencies, reducing costs, and enhancing adaptability to better support evolving demands.

KEY SUPPORTING TECHNOLOGIES

Grid modernization will be fueled by technological advances in a range of areas. Here are a couple of the technology categories that are fueling the grid's evolution:



Grid-enhancing technologies (GET).
GET represents a layered set of tools and technologies that improve the efficiency, capacity, visibility, and responsiveness of the existing electrical grid infrastructure. These technologies can include advanced software, sensors, and power electronics that can enable improved operations. For example, these technologies can improve energy distribution by identifying inefficiencies and adjusting power flow dynamically.

AI applications.
AI will continue to play an increasingly central role in grid operations. AI-driven innovations will fuel enhancements in grid management, load balancing, flow prediction, market exchanges, and more.

POWER GRID GROWTH AND EVOLUTION PRESENT UNPRECEDENTED DEMANDS FOR CAPACITORS

As power grids expand and modernize, the demand for high-performance capacitors has surged. Capacitors are essential components in power transmission and distribution systems, supporting voltage stability, power factor correction, and energy storage. The global market for high-voltage direct current (HVDC) capacitors is projected to grow at a compound annual growth rate (CAGR) of 13.8%, reaching $17.9 billion by 2031.[2]

DEMANDS ON HIGH-VOLTAGE CAPACITORS

As demands on grids continue to grow, more capacitors will be essential. However, when it comes to capacitors, grid operators won't be successful with more of the same. The evolution of power grids introduces intensifying demands for high-voltage capacitor technologies that support:

- **Higher energy loads.** As power systems carry greater loads, capacitors must handle increased energy storage and dissipation requirements without compromising performance.
- **Cost and resource efficiency.** Grid operators need to scale capacity but do so affordably. These organizations need capacitors that are compact, cost effective, and long lasting so they can maximize the returns on their investments.
- **Temperature resilience.** As the grid continues to evolve and support more transmissions, equipment will run hotter. Capacitors must withstand temperatures exceeding 150 °C to ensure reliable performance in high-stress environments.
- **High reliability and long lifespan.** With higher grid complexity and fluctuating energy demands, capacitors must provide long-term reliability to minimize maintenance costs and downtime.

[2] Markets and Markets, "HVDC Capacitor Market," August 2023, URL: https://www.marketsandmarkets.com/Market-Reports/hvdc-capacitor-market-175421495.html

LIMITATIONS OF BOPP CAPACITORS

Biaxially oriented polypropylene (BOPP) capacitors have been the industry standard for decades. Today, however, these technologies present several limitations that hinder grid modernization efforts:

- **Insufficient thermal tolerance.** Traditional BOPP capacitors struggle to operate above 105 °C, whereas modern grids demand thermal resilience exceeding 150 °C.
- **Low dielectric constant.** BOPP materials offer a limited dielectric constant, restricting their ability to scale energy storage capacity efficiently.
- **Supply chain vulnerabilities.** With approximately 80% of global BOPP film production concentrated in China, manufacturers are exposed to supply chain disruptions and spiraling costs.
- **Size and weight constraints.** BOPP capacitors often require larger form factors, making them less viable for space-constrained applications in modern power grids.

WITH APPROXIMATELY 80% OF GLOBAL BOPP FILM PRODUCTION CONCENTRATED IN CHINA, MANUFACTURERS ARE EXPOSED TO SUPPLY CHAIN DISRUPTIONS AND SPIRALING COSTS.

13.8%

GROWTH

OF POWER CAPACITORS

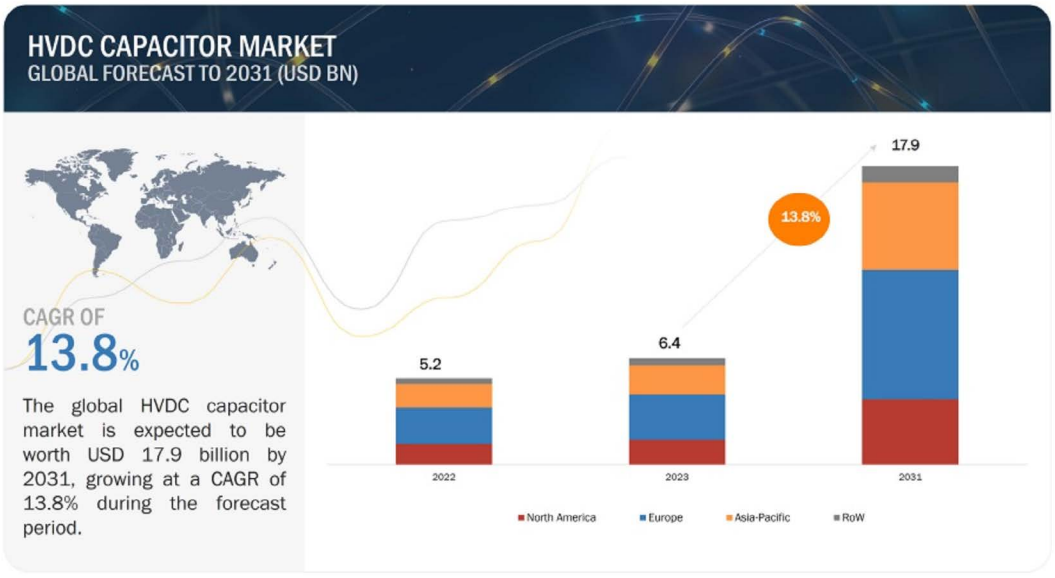
MARKET OPPORTUNITY

The growing need for innovative, high-voltage capacitors presents a lucrative market opportunity for manufacturers. By addressing evolving grid demands with advanced capacitor technologies, companies can secure a competitive advantage in the rapidly expanding energy sector. Capacitor manufacturers who adopt next-generation materials will be well positioned for long-term success.

HIGH VOLTAGE POWER CAPACITOR MARKET

The market opportunity for high-voltage power capacitors is expected to **grow by 13.8% (13.8% Growth)** over the next five years and reach USD 17.9B. This increase will be driven by global demand for energy and the need to upgrade the grid to a more intelligent AI-enabled infrastructure.

BY ADDRESSING EVOLVING GRID DEMANDS WITH ADVANCED CAPACITOR TECHNOLOGIES, COMPANIES CAN SECURE A COMPETITIVE ADVANTAGE



Source: MARKETSANDMARKETS– HVDC Capacitor Market Size, Share & Analysis

NANOPLEX

NANOPLEX™

PEAK NANOPLEX FILMS:
ADVANCING CAPACITOR TECHNOLOGY FOR MODERN GRIDS

Today, Peak offers the advanced films that enable capacitor manufacturers to deliver advanced, high-voltage capacitors and capitalize on the massive market opportunities presented by the modernizing grid. With Peak NanoPlex films, capacitor manufacturers can deliver the capacitors that help make the grid smarter, stronger, and more adaptable.

NanoPlex films enable breakthroughs in capacitor technology, providing enhanced thermal stability, superior energy density, and greater durability compared to traditional BOPP capacitors. NanoPlex films are helping modernize grid infrastructure by enabling compact, high-performance energy storage at every level of the grid, including generation, transmission, and distribution.

By integrating NanoPlex technology into high-voltage capacitors, capacitor manufacturers can address an urgent market demand. With these offerings, grid operators can achieve superior performance, reduce maintenance costs, and enhance grid stability. Peak delivers these offerings:

NANOPLEX™ LDF

NANOPLEX LDF CAPACITOR FILMS.

Low Dielectric Film (LDF) provides exceptional thermal stability, low dielectric loss, and high voltage breakdown strength. LDF enhances component longevity and ensures stable performance under fluctuating load conditions.

NANOPLEX™ HDC

NANOPLEX HDC ULTRA-HIGH-POWER FILMS.

High Dielectric Constant (HDC) film delivers superior capacitance in a reduced footprint, making it ideal for applications where space and efficiency are at a premium. HDC enables rapid charge/discharge cycles and superior filtering performance, supporting the transition to high-frequency, high-efficiency power electronics.

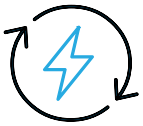
ADVANTAGES OVER BOPP

Compared to traditional BOPP films, **NanoPlex films** offer these advantages:

Higher energy storage. HDC nanolayered technology enables up to four times more energy storage.

Reduced footprint. HDC capacitors are up to 50% smaller and lighter, enhancing efficiency and reducing impedance.

Longer lifespan. LDF extends capacitor life up to five times longer than conventional options.

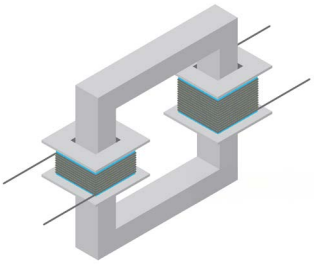


Higher duty cycles. LDF enables three to five times higher duty cycles, making it ideal for high-performance applications.

Bill of materials (BOM) savings. HDC delivers significant cost advantages, enabling capacitor manufacturers to cut BOM costs in half.

Superior temperature tolerance. LDF withstands temperatures up to 135 °C, exceeding conventional films by more than 30 °C.

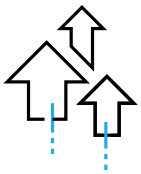
AREAS OF APPLICATION: HOW PEAK CAN HELP ADDRESS KEY USE CASES



Grid operators are struggling to address the key imperatives presented by grid modernization. These organizations need advanced capacitors that play a central role in promoting grid modernization and scale. By leveraging Peak NanoPlex films, capacitor manufacturers can address this urgent market demand. Capacitors that feature Peak technologies can enable breakthroughs in a range of areas. The following sections explore these areas in more detail.

STEP-UP/STEP-DOWN POWER

Step-up and step-down power transmission systems are essential for ensuring that electricity is delivered efficiently and safely across different segments of the power grid. These systems regulate voltage for both long-distance transmission and localized distribution, playing a critical role in mobile and modular power solutions. At the heart of these systems, capacitors are indispensable for insulation, energy storage, and voltage stabilization.



ENHANCE CAPACITOR PERFORMANCE IN GRID APPLICATIONS.

How Peak Can Help

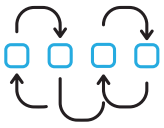
Peak's LDF and HDC films significantly enhance capacitor performance in grid applications. LDF film offers high thermal stability, ensuring capacitors maintain dimensional and dielectric integrity even at elevated temperatures. Additionally, LDF's low dielectric loss improves energy efficiency, particularly in step-up transformers where minimizing energy dissipation is crucial for long-distance power delivery. Featuring higher breakdown voltage, LDF capacitors enhance system reliability and reduce maintenance requirements.

Similarly, HDC film provides a substantial boost in energy density, enabling compact and highly efficient capacitor designs. Its enhanced voltage-smoothing capabilities contribute to a more stable power grid. Moreover, HDC films excel in emerging high-frequency applications. By integrating HDC-enabled capacitors, grid operators can improve overall transformer efficiency, especially in dynamic load environments or grids with fluctuating input from renewables.

PEAK'S LDF AND HDC FILMS SIGNIFICANTLY ENHANCE CAPACITOR PERFORMANCE IN GRID APPLICATIONS.

HYBRID POWER FACTOR CORRECTION (PFC)

Hybrid PFC solutions combine passive and active correction techniques to manage load conditions, reduce harmonic distortion, and improve voltage stability. These systems are critical for integrating renewable and distributed energy resources while adhering to evolving interconnection standards. As the modern grid continues to grow increasingly reliant on hybrid PFC systems to maintain power quality, the need for advanced capacitor technology has never been greater.



RELIABLE OPERATION IN HIGH-FREQUENCY SWITCHING ENVIRONMENTS

How Peak Can Help

Peak's LDF and HDC films enable the delivery of a new generation of hybrid PFC capacitors. LDF's low dielectric loss makes it particularly effective in active PFC circuits, allowing for reliable operation in high-frequency switching environments. Its superior thermal stability ensures extended operational life, even in rapidly changing conditions.

HDC film complements these benefits by providing higher energy density and low equivalent series resistance, making it ideal for compact passive PFC applications. HDC solutions respond swiftly to load fluctuations, ensuring high power factor maintenance in dynamic environments. Together, LDF and HDC enable a balanced approach to hybrid PFC, supporting the delivery of smaller, more efficient, and more reliable correction systems.

MOBILE POWER GRID

Mobile power systems are essential for disaster recovery, maintenance support, events, military and defense operations, and more. These systems require capacitors that can withstand extreme conditions, fluctuating loads, and compact design constraints

MAINTAINING HIGH THERMAL STABILITY

How Peak Can Help

LDF film capacitors excel in harsh environments, maintaining high thermal stability in environments where conventional films, such as BOPP, fail. Their durability and lightweight nature make them ideal for mobile applications, reducing overall system weight while ensuring mechanical integrity. Capacitors that leverage LDF offer long lifecycles and low maintenance, reducing the logistical strain of having to do replacements in remote deployments.

Mobile trucks equipped with HDC-based capacitors can provide immediate voltage support to substations during maintenance, emergencies, or temporary events. Their high energy density and compact footprint allow for more space- and resource-efficient mobile grid configurations. By enabling enhanced voltage regulation and rapid response to dynamic loads, HDC film capacitors improve the resilience and efficiency of mobile energy platforms. Together, these films support breakthroughs in energy mobility, where resilience and efficiency aren't optional—they're imperatives.

SUBSTATIONS

EXCELLENT THERMAL AND ELECTRICAL STABILITY

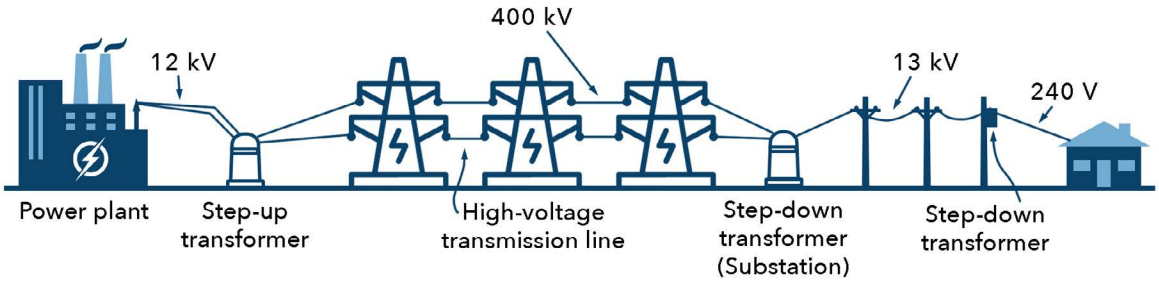
Modern substations rely on capacitors for a variety of functions, including voltage regulation, reactive power compensation, and transient voltage suppression. As substations transition to more compact, modular, and high-efficiency designs, capacitor performance is increasingly crucial.

How Peak Can Help

LDF capacitors provide excellent thermal and electrical stability, making them well suited for substation environments in which temperature fluctuations and electrical surges are common. Their low dielectric loss ensures long-term energy efficiency, while high durability contributes to extended service life and reduced maintenance.

HIGHER ENERGY DENSITY

HDC capacitors enhance substation performance by offering higher energy density and rapid charge-discharge capabilities. This is especially valuable in dynamic load conditions, where fast-response capacitors support voltage stabilization, peak shaving, and frequency regulation. The compact nature of HDC film capacitors makes them ideal for mobile or containerized substations, supporting the evolving needs of modern grid infrastructure. By leveraging LDF and HDC, substations can become more efficient, compact, and resilient.



TECHNOLOGIES PEAK ENABLES

SSTs

Solid-State Transformers
Solid-state transformers (SSTs) are revolutionizing grid modernization. Increasingly, these semiconductor-based power conversion devices are replacing traditional magnetic-core transformers. These transformers provide higher efficiency, bidirectional power flow, and modular scalability. SSTs rely on advanced capacitor technologies for voltage stabilization, filtering, and energy storage.

How Peak Can Help
LDF film capacitors ensure high-frequency reliability in SST applications, reducing dielectric losses and thermal buildup while maintaining mechanical stability. HDC enables the delivery of capacitors that enhance SST performance, offering high energy density, rapid energy discharge, and superior voltage regulation. Together, LDF and HDC enable capacitor manufacturers to create compact, efficient, and reliable capacitor banks tailored for SST modules.

HIGH ENERGY DENSITY, RAPID ENERGY DISCHARGE, AND SUPERIOR VOLTAGE REGULATION.

HSF

High-Frequency Switching
High-frequency switching (HFS) is a critical component of modern power electronics, allowing for more efficient energy conversion and management. HFS devices operate at much higher switching frequencies than traditional power systems—typically in the range of tens of kilohertz (kHz) to several megahertz (MHz). Capacitors used in HFS devices must withstand rapid switching cycles, high temperatures, and elevated voltage stress.

How Peak Can Help
LDF film capacitors minimize dielectric losses at high frequencies, ensuring efficient operation while maintaining long-term reliability and durability. HDC film capacitors provide low equivalent series resistance, high ripple current handling, and fast energy discharge, making them ideal for compact, high-frequency modules. By incorporating Peak's LDF and HDC films, capacitor manufacturers can develop cutting-edge solutions for HFS applications, powering the next wave of power grid innovation.

ENSURING EFFICIENT OPERATION WHILE MAINTAINING LONG-TERM RELIABILITY AND DURABILITY

HOW YOUR ORGANIZATION CAN PROFIT

Capacitor manufacturers that leverage NanoPlex films can realize several significant benefits:

- **Gain clear differentiation.** Peak's innovative capacitor films provide a clear competitive advantage by enabling the development of power grid solutions that are higher performing, more compact, and more cost-effective. With LDF and HDC, manufacturers can differentiate their offerings, delivering up to four times more power in half the footprint of traditional capacitor designs.

- **Boost profits and margins.** Peak LDF and HDC films deliver significant cost savings, reducing film costs as well as operations and maintenance expenses. By cutting bill-of-materials costs by 60% and lowering expenses, Peak's technologies can contribute to estimated savings of $3.4 billion over a 30-year lifespan.

- **Mitigate supply chain complexity and risk.** As outlined above, 100% of BOPP films are produced outside of the US, with 80% of supplies coming from China. For US-based manufacturers, this reliance on international vendors can introduce increased cost and risk. Peak helps mitigate these supply chain risks, as 100% of its film production and supply chain operations are based in the US.

CONCLUSION

Peak NanoPlex films are transforming capacitor technology, providing manufacturers with the tools to enhance grid efficiency, reliability, and scalability. With higher energy density, improved thermal stability, and cost advantages, NanoPlex films empower grid modernization efforts across multiple applications. By adopting Peak's advanced films, capacitor manufacturers can gain a competitive edge, boost profits, and fuel innovation in power grid infrastructures.

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