



# Analysis of Efficiency Optimization in Power Transmission and Distribution Using Power Electronic Technology

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**Abstract.** Nowadays, the demand for better efficiency, flexibility and reliability in modern power systems is rising gradually, to prompt the wide application of advanced power electronic technology in transmission and distribution. This dissertation aims to explore how these technologies have developed from conventional silicon devices to wide **bandgap** (WBG) materials like silicon carbide (SiC) and gallium nitride (GaN), and also analyses the effect of flexible AC transmission systems (FACTS) and smart grids in improving system performance. By boosting the switching speed, lowering conduction losses and real-time monitoring, these innovations can reduce line losses by up to 20% and dramatically improve overall system stability. According to the latest studies about converter design and real cases, this dissertation analyses key factors such as cost, thermal management and compatibility with legacy equipment. Moreover, it also emphasizes how robust control algorithms and data-driven approaches optimise power delivery. Research results show that combining advanced materials, flexible operation strategies and smart automation can effectively solve key bottlenecks like low transmission efficiency and poor stability, promoting the development of high-efficiency, reliable and sustainable power networks. This study proposes a path to achieve these advantages from the system level to build a cleaner and more resilient future energy system.

**Keywords:** Power Electronics, Flexible Ac Transmission System (Facts), Wide Bandgap(Wbg), Smart Grid

## 1 Introduction

With global energy consumption increasing gradually and renewable sources such as wind and solar power rapidly developing, traditional centralized power generation and long-distance AC transmission have become no longer ideal. Long-distance AC transmission lines are prone to high energy losses, and systems with only basic control strategies are unable to cope with the fluctuating demand for power flow. In this background, power electronics technology is developing rapidly as a key enabling technology, with fast switching and intelligent control strategies that can effectively support modern power grid demands. By pressing regulation of voltage levels and bi-directional power flow, power electronics technology can significantly promote the

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stability and efficiency of power transmission. The development of power electronics began with vacuum tube devices but limited applications due to large size, short life and application scenarios. With the advent of silicon-based devices especially silicon-controlled rectifiers (SCRs), greatly reducing equipment size and increasing reliability. After this, the development of bipolar junction transistors (BJTs) and metal-oxide-semiconductor field-effect transistors (MOSFETs) further expanded the application scope of power conversion, improving switching speed and control options. However, with the demand for higher power density and fast switching capabilities increasing, traditional silicon components are gradually reaching performance bottlenecks. To meet the requirements of higher efficiency and stronger robustness WBG materials like SiC and GaN were applied to electronic power systems. These WBG materials have higher breakdown voltages, better thermal conductivity and lower energy losses. It is currently being gradually applied to scenarios such as electric vehicle charging stations and data centre power supplies. In addition to advances in semiconductor materials, innovations in converter topology and control algorithms have also reshaped transmission and distribution (T&D) strategies. A typical example is FACTS, which uses voltage source converters (VSCs) to control active and reactive power independently. This is especially essential in grid-connected offshore wind power and other intermittent energy sources because it is often far away from the load centre. FACTS can reduce transmission losses and stabilize voltages along lengthy corridors by rapidly adjusting the power flow. Meanwhile, the rise of smart grids introduces sensors, automated reconfiguration and data analytics into power systems. These technologies allow operators can detect and isolate faults more quickly, balance fluctuation in solar or wind power, and even avoid local overload by adjusting the path. Despite the promising future, the development of power electronics still faces some challenges. The cost of upgrading older transformers, switch devices and protect devices is expensive, simultaneously, careful design is required to ensure the compatibility of the high-frequency converter with the synchronous generator. If the old and new equipment are not coupled properly, it may cause some problems like electromagnetic interference or transient stability. Additionally, the cost of WBG components remains expensive, and efficient thermal management is also complex at high power density. Therefore, close collaboration between academia, manufacturers and power companies is needed to cope with multiple barriers at the technical and application levels.

## **2 Development of Advanced Power Electronics Technology**

### **2.1 Advancements in Power Electronic Devices and Their Role in Modern Grids**

The development of power electronic technology has experienced several stages. The first stage is called the vacuum electronics era (from the early 20th century to the 1950s). In the early 20th century, electronic tubes like vacuum diodes were controlled by power, but their application was limited due to their large size, low efficiency and short life. During the 1930s, mercury arc rectifiers began to be used in high-power

rectification applications which highly increased the efficiency of power conversion. The next stage was the semiconductor era (from the 1950s to 1990s). In the 1950s, significant breakthroughs in semiconductor technology led to the development of point contact transistors and junction transistors, laying the foundation of power electronics. In 1955, General Electric in the United States introduced the world's first silicon rectifier (SR) using monocrystalline silicon as the semiconductor rectifying material, and in 1957, it launched the world's first silicon-controlled rectifier (SCR) for power conversion and control applications [1]. From the 1960s to 1970s, SCR was widely used in rectification, motor control, speed regulation and other fields, leading to the development of high-voltage direct current (HVDC) transmission and alternating current (AC) motor drives, the mercury arc rectifiers were gradually replaced by semiconductor devices. During this period power conversion technology mainly used phase-controlled rectification. Although it achieved basic AC to direct current (DC) conversion, it also had problems like low efficiency and harmonic pollution. In the 1970s, bipolar junction transistors (BJT) were used in power electronic systems, but their application was limited by their slow switching speed and high driving power. In the 1980s, metal-oxide-semiconductor field-effect transistors (MOSFET) developed rapidly, offering high-speed switching and low drive power, especially suitable for low-power applications. In the late 1980s and 1990s, the development of insulated gate bipolar transistors (IGBT) combined the advantages of MOSFET and BJT, allowing for high voltage and high-efficiency operation. This invention greatly expanded applications in power electronic technology. Enter the 21st century, power electronic technology has evolved toward high efficiency, intelligence, and modularization. With the advancement of materials science and microelectronics technology, wide bandgap semiconductors (WBGs) like silicon carbide (SiC) and gallium nitride (GaN) rose gradually. Compared with traditional silicon devices, WBG devices (such as SiC) can handle about 10 times the breakdown voltage, reduce switching losses by up to 50%, and provide nearly three times higher thermal conductivity, which makes high power density and high-frequency applications possible. Furthermore, the development of a flexible AC transmission system (FACTS) greatly reduced the loss of electric energy in long-distance transmission, especially in the new energy power generation and urban distribution network that has been widely applied. Simultaneously, smart grid technology combines big data, artificial intelligence (AI), and Internet of Things (IoT), which made the real-time monitoring and adaptive adjustment of power come true, pushing the application boundary of power electronics technology.

The development of these technologies not only promotes the efficiency of power conversion but also offers more possibilities for power system integration. Nowadays, from efficient energy converters to intelligent control systems, power electronics technology has become an indispensable and important part of modern power systems. It will directly affect the optimization level of future power transmission and distribution systems with its continuous progress. Today, the field of power electronics is propelled by two converging forces: the need for high-performance, low-loss devices, and the increasing complexity of power networks integrating renewable. Researchers continue to push the boundaries by experimenting with new materials and converter architectures. As demands for more robust, efficient, and flexible grids grow, so does

the urgency for advanced power electronics that can seamlessly interface different voltage levels, frequencies, and energy sources. These advancements have laid the foundation for cutting-edge applications such as WBG devices and voltage source converter-based HVDC (VSC-HVDC) systems.

## 2.2 Current cutting-edge technology

**WBGs.** WBG materials, notably SiC and GaN, enable power electronic devices to operate at higher voltages, frequencies, and temperatures compared to traditional silicon-based components. Recent advances summarized in the 2022 survey by Kumar et al. confirm that WBG devices can cut switching losses by up to 50% and tolerate junction temperatures above 200 ° C [2]. By minimizing conduction and switching losses, they often achieve substantially better performance in high-power applications. These gains can translate into more compact converters, lower cooling requirements, and enhanced efficiency, especially in settings where space or thermal management poses constraints.

Continuous improvements in crystal growth and packaging have begun to reduce the manufacturing cost of SiC and GaN devices. Although still more expensive than silicon parts, WBG modules are increasingly adopted in renewable energy inverters, electric vehicle power systems, and data centre power supplies that prioritize optimal efficiency. Today, WBG semiconductors are steadily becoming commercialized and have demonstrated huge efficiency improvement potential in high-performance inverters, uninterruptible power supplies, solid-state transformers, and other applications.

**FACTS.** FACTS employ voltage source converters (VSCs) capable of independent control overactive and reactive power. By avoiding line-commutated thyristors, these setups incur fewer harmonic issues and enable smoother integration with weak grids [3]. In scenarios such as long-distance transmission of offshore wind power, VSC-HVDC lines can effectively reduce losses and simplify the voltage regulation process. A notable example is Germany's DolWin3 project, which utilizes VSC-HVDC to transmit 900 MW of offshore wind power over 160 km with reduced losses and improved grid stability [4].

Different from conventional point-to-point HVDC, flexible AC allows multi-terminal topologies, facilitating power routing among several stations. In the face of intermittent renewable, operators can reroute flows dynamically to maintain stability. Although the engineering difficulty is relatively higher, this approach provides greater adaptability and scalability for large-scale green energy projects.

**Smart Grid Technology.** Smart-grid evolution is no longer limited to AMI roll-outs; the 2024 review by Kiasari et al. highlights the convergence of machine learning-based forecasting with large-scale battery energy-storage systems, demonstrating voltage-regulation errors below 1 % in field pilots [5]. Smart grids integrate advanced communication, sensor technology, and automated control into conventional power

networks. Power electronics devices, such as intelligent inverters and solid-state transformers, support real-time adjustments to voltage and frequency, helping to prevent overloads and local power quality issues. When distributed resources like rooftop solar or community-scale storage are present, these devices also coordinate two-way power exchange to balance the system.

Furthermore, microgrid deployments rely on power electronics to function autonomously when disconnected from the main grid. High-speed converters play an important part in load sharing and fault isolation, ensuring that the system continues to supply power during a grid outage and is smoothly connected to the larger grid after restoration. By a mature control algorithm, microgrids can re-synchronize with the larger grid seamlessly once normal conditions are restored.

### **3 Efficiency Issues in Power Transmission Distribution**

#### **3.1 Traditional system efficiency bottleneck**

Many traditional power systems were designed with centralized thermal power or hydropower stations, leading to long transmission lines, which cause voltage drops and reactive power problems. Operators generally use capacitors, inductors, or synchronous condensers to adjust these problems. However, these methods often increase the complexity of the system. With the continued growth in load, the pressure in old transformers and switchgear had increased, especially in peak electricity consumption is prone to inefficiency problems. Furthermore, it is difficult to flexibly respond to access to renewable energy such as wind and solar energy by using a power grid with a fixed structure and lack of real-time monitoring and automatic control. The lack of automated controls and advanced converter interfaces increases the risks of voltage instability or frequency fluctuation. The lack of modern equipment, even partial load operations can lead to disproportionate energy loss highlights the necessity of refined transformation.

#### **3.2 Main sources of losses**

The resistive losses remain a main challenge in long-distance AC power grids, accounting for approximately 6-8% of global AC system power losses. When current is transmitted in long lines, part of the electrical energy will convert into heat lowering the overall efficiency in the system because of the resistors. In areas where load centres are expanding rapidly, the problem will be exacerbated by ageing lines or imperfect materials, leading to noticeable voltage drops and rising operating costs. Although upgrading conductors or installing additional lines can alleviate these problems, such infrastructure projects can be capital-intensive and require lengthy approval processes.

Transformers introduce another significant source of inefficiency, particularly when outdated core materials or designs are used. Both no-load losses (core losses) and load losses (copper losses) can be substantial if the transformer runs continuously under partial load conditions [6]. Some older transformers also lack advanced cooling mechanisms, allowing temperatures to rise and causing further degradation over time.

For instance, studies in India have shown that oil-immersed transformers over 50 years old can suffer from no-load (core) losses as high as 1.5%. These factors not only consume additional energy but may also shorten the service life of equipment, necessitating more frequent maintenance or premature replacement.

Apart from hardware constraints, poor power factor management contributes to further inefficiencies. When loads draw significant reactive power, the resultant increase in current raises conduction losses in cables and transformers. Traditional solutions, such as installing capacitor banks, can partially offset reactive power demand, but if the configuration is uncoordinated or the capacity is oversized, may cause voltage regulation difficulties and unnecessary circulating current problems. This situation is particularly prominent in industrial and commercial distribution networks where characteristics vary significantly. Additionally, system unbalances—whether between phases or between feeders will lead to uneven current distribution, forming local hot spots in the conductors and exacerbating losses. In some power grids, low automation levels or backward protection mechanisms will delay failure response, making low efficiency continue to persist. With modern grid transformation towards distributed generation and renewable energy fluctuation access, it is essential to have a comprehensive monitoring, control and asset upgrade strategy. Ultimately, collaborative optimization through equipment modernization, reactive power coordination and real-time load balancing can significantly reduce system losses and improve overall system performance.

## **4 Application of Cutting-edge Technologies in Efficiency Optimization**

### **4.1 High-Efficiency Converter Techniques**

Generally, both switching strategy and thermal management need to be optimized to raise the efficiency of power converters. A comparative study in 2024 found that advanced space vector PWM (SV-PWM) variants can reduce common-mode EMI by 8–12 dB without sacrificing efficiency [7]. Rather than focus on theoretical improvements in semiconductor materials, practical applications should concentrate on reducing conduction losses, minimizing electromagnetic interference and improving cooling path design [8]. For example, soft-switching technology like zero-voltage switching (ZVS) and zero-current switching (ZCS) can reduce voltage surges, and the resonant circuit helps to keep the waveform smooth when the load fluctuates. In multiple industrial scenarios, using predictive control algorithms makes the converter dynamically adjust according to real-time needs to maintain high efficiency in different loads. Additionally, optimized PCB layout and selected passive components can lower stray inductance to further reduce energy loss and improve reliability in high frequency switching operations.

## 4.2 WBG Device Integration

The application of WBG devices like SiC and GaN in reasonable system architecture and packaging can bring significant performance advantages. In large-scale applications, based on WBG power modules can support higher switching frequency and operating temperature, which contribute to minimizing the size of the converter [9]. However, improving efficiency not only depends on the device material itself but also requires supporting drive circuits, advanced heat dissipation structure and comprehensive electromagnetic compatibility testing. System-level design becomes crucial to maximizing the return on investment of WBG devices. For example, selecting the appropriate gate driver can ensure stable operation under high-speed switching, and embedded thermal sensors help prevent temperature overshoots. These measures contribute to extending device life and enhancing converter output stability to reduce the cost of operation and maintenance.

## 4.3 Flexible HVDC Implementation

Flexible HVDC projects have been deployed globally to meet the needs of long-distance power transmission and reduce line losses simultaneously. In practical operation, VSCs can regulate power flow in both active and reactive aspects to cope with changing load patterns or fluctuations in renewable energy output [10]. In real engineering, more attention is paid to modular scalability and the ability to cope with unexpected grid conditions instead of repeating the theoretical content of HVDC. From a practical perspective, flexible HVDC stations integrate multi-level protection solutions dedicated filtering systems and real-time monitoring to mitigate some issues such as overload or potential harmonics. As the power grid expands, more wind power or photovoltaic power plants are connected to regions that are far away from load centres, these stations can work as a flexible backbone facility to reroute power transmission rapidly when some power generation sites may experience sudden power outages or failures.

## 4.4 Smart Grid Applications and Automation

In a smart grid environment, advanced power electronics technology enhances automation level and distributed energy management capabilities. Current applications should focus on how these devices support micro-grid autonomous operation and rapid fault isolation rather than repeating the basic design of intelligent inverters or transformers [11]. For instance, real-time data analytics and digital communication protocols enable distribution feeders to operate with little to no human intervention, and they can adjust the voltage set point automatically and dispatch reactive power compensation to maintain the power quality. When integrated with sensor-based conventional substations, power electronics technology can also respond to local overloads, enabling automatic load shedding or reconfiguration. Such adaptive measures reduce downtime, particularly in urban environments where critical loads must remain online. In combination with battery energy storage, converters in a smart

grid can perform peak shaving, frequency regulation, and transient smoothing, thus lowering strain on central dispatch systems. As these automated mechanisms mature, they pave the way for self-healing grids capable of detecting anomalies and isolating them before cascading failures occur.

## **5 Technical Challenges Proposed Solutions**

### **5.1 Cost and Economic Viability**

Transitioning to advanced power electronics often entails a noticeable gap between initial outlay and eventual savings. Organizations planning to replace legacy components with WBG-based converters or flexible DC infrastructures may face elevated procurement costs due to specialized manufacturing and stringent testing. In regions with tight budgets, allocating capital for these newer technologies can be challenging, leading decision-makers to question feasibility before tangible benefits become evident.

However, research and pilot studies continue to underscore the potential for long-term gains, including lowered line losses, reduced maintenance routines, and fewer equipment replacements [12]. To alleviate the economic pressure on individual units, people are also exploring financing forms such as public-private partnerships or performance-based contracts to share risks through a multi-party sharing model. With the scale effect and the maturity of production technology, the price of new-generation power electronic devices tends to decrease, making them more competitive in the market.

### **5.2 Stability and Thermal Management**

In modern grids, converters operate at high switching frequencies and power densities, raising substantial concerns about heat dissipation and interference. According to the latest 2025 review, model-predictive-controlled single-phase PV inverters can keep total harmonic distortion below 2 % even under rapidly varying irradiance [13]. If not managed in time, even small energy losses in semiconductor devices can produce enough heat to reduce system performance or shorten device lifespans. Therefore, engineers usually prioritize efficient cooling solutions, such as advanced liquid or vapour-phase systems, with carefully designed packaging structures to avoid hot spot accumulation. Apart from thermal management issues, stability challenges appear when these high-speed switching devices operate with older synchronous generation equipment or unbalanced distribution networks [14]. Rapid transient changes may cause voltage spikes or harmonic distortions, which affects the normal response of traditional protection devices. To mitigate these effects, real-time monitoring systems and electromagnetic compatibility (EMC) countermeasures must be deployed. These measures include strengthening shielding and reasonable filter placement, even introducing prediction algorithms to discover abnormalities in time before the fault expands to avoid power grid interruption.

### 5.3 Practical Implementation and Performance Evaluation

Rubio et al. report that IEC 61850 digital substations equipped with AI relays reduce average fault clearing time by approximately 35% [15]. A standardized evaluation framework also ensures consistency in indicators, making stakeholders objectively compare results [16]. Cross-sector collaboration plays a crucial part in promoting technology implementation. Equipment manufacturers and electric power companies should often collaborate with research institutions and policymakers [17]. Such approaches mitigate investors' concerns while shortening approval timelines [18]. Based on the success of the pilot project, automatic or semi-automatic configuration can be extended from micro-grid to the entire regional grid, stable response to the grid connection needs of intermittent energy [19]. Ultimately, standardized documentation and transparent results reporting can promote continuous improvement mechanisms, promoting the innovative evolution of advanced power electronics technology.

## 6 Conclusion

In summary, advanced power electronics technology provides many possibilities for improving the efficiency of power transmission and distribution systems. WBG devices, such as SiC and GaN perform outstandingly in reducing losses because they have faster switched speed and higher voltage resistance. These technologies are especially suitable for large-scale renewable energy power plants and high-load scenarios, where reducing energy waste is crucial. Simultaneously, FACTS offer a flexible way to control power flow, which can balance active and reactive power to reduce line losses and simplify the process of connecting offshore wind power and other remote power sources to the grid. By integrating these new devices and systems into the smart grid framework, their potential will be further unleashed. Real-time data collected by sensors throughout the power grid can provide support for automated decision-making on voltage, frequency and fault management. High-speed inverters and solid-state transformers not only enhance operation efficiency but also help the system adapt to load and power fluctuations rapidly. Supporting advanced power electronics technology, micro-grid can operate independently when the main network fails and reconnects smoothly after recovery, which significantly improves system reliability. However, there are still many challenges in actual deployments, including the expensive cost of WBG components, hard to retrofit old equipment and the need for efficient heat dissipation methods. Solving these problems needs continuous investment in scientific research, large-scale pilot verification and close collaboration between technology suppliers and grid operators. With the energy landscape evolving towards more distributed and digital solutions, power electronic technology will play an important part in contributing to a cleaner, safer and more adaptable power system. As long as all parties work together, overcoming technical and economic challenges in an orderly manner can fully unleash the potential of these advanced technologies to lay the foundation for building a more sustainable and efficient power system in the future.

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