

Chapter 4

The Role of Electrical Engineering in Renewable and Smart Energy Systems

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1. Introduction

The integration of renewable energy sources, such as solar and wind, into existing power grids presents unique challenges, particularly in the areas of energy storage, system stability, and protection. As renewable sources are often intermittent, meaning they are not always available when demand peaks, the need for advanced energy storage solutions has never been more critical. Energy storage plays a pivotal role in ensuring that excess energy generated during periods of high production can be stored for later use, maintaining a stable supply even when renewable generation is low. By addressing the fluctuating nature of renewable energy, energy storage solutions help balance supply and demand, ensuring that the grid remains resilient and efficient.

Alongside storage, advanced control systems are essential for managing the complex dynamics of modern power grids. The integration of diverse renewable energy sources and the increasing deployment of smart technologies require sophisticated control mechanisms to ensure optimal energy flow and grid stability. These systems must be capable of regulating power quality, balancing generation with demand, and responding to sudden fluctuations in supply or demand. Advanced control strategies, including real-time monitoring, predictive analytics, and automated responses, are essential to avoid grid instability and enhance the overall efficiency of renewable energy systems.

In addition to the need for advanced control, power system protection is a fundamental component in maintaining the safety and reliability of energy networks. Renewable energy systems, especially those that involve distributed generation, introduce new complexities in terms of fault detection, isolation, and recovery. Traditional protection methods may not be suitable for the unique characteristics of renewable energy technologies. Thus, innovative protection strategies, tailored to address the specific challenges posed by renewable energy integration, are necessary to prevent system failures, mitigate potential risks, and protect both grid infrastructure and consumers.

The development of energy storage technologies, advanced control systems, and power system protection mechanisms is therefore interdependent. Effective energy storage solutions are often paired with sophisticated control systems to manage how stored energy is dispatched into the grid at the right time. Simultaneously, the protection mechanisms ensure that the grid remains secure during

transitions between renewable and traditional energy sources. Together, these elements form the backbone of a resilient, reliable, and efficient power system that can support the large-scale integration of renewable energy.

As the world transitions towards cleaner, more sustainable energy sources, the role of electrical engineering in solving these challenges is becoming ever more vital. Engineers are at the forefront of designing systems that can seamlessly integrate renewable energy, ensure grid stability, and provide the necessary protection to keep the power flowing safely. Through continued innovation in energy storage, advanced control systems, and power system protection, the path to a greener, more reliable energy future is becoming increasingly achievable

2. Energy Storage Solutions and Grid Stability

Energy storage solutions are critical in enabling the efficient integration of renewable energy sources into the power grid. Renewable sources like solar and wind are intermittent, meaning their energy output fluctuates depending on weather conditions and time of day. This variability presents significant challenges for grid operators, who must maintain a stable and reliable electricity supply to meet demand. Energy storage systems (ESS) provide a way to store excess energy generated during periods of high production and release it when demand is high or generation is low, ensuring grid stability. This section will explore various energy storage technologies and their role in enhancing grid stability, as well as the challenges associated with their integration.

2.1. Types of Energy Storage Systems

There are several types of energy storage systems, each with distinct characteristics, advantages, and applications. The most common technologies include batteries, pumped hydro storage, compressed air energy storage (CAES), and flywheels.

- **Batteries:** Batteries, particularly lithium-ion (Li-ion) batteries, are the most widely used energy storage technology due to their high energy density, scalability, and declining costs. These batteries store energy by converting electrical energy into chemical energy and can discharge that energy back into the grid when needed. Batteries are particularly effective in grid stabilization for short-term fluctuations and are essential for supporting renewable energy integration by providing backup power during peak demand periods or when generation is low.
- **Pumped Hydro Storage:** This is one of the oldest and most widely used large-scale energy storage technologies. It involves storing energy by pumping water from a lower reservoir to an upper reservoir during periods of low demand or high generation. When energy is needed, the stored water is released, flowing down to the lower reservoir through turbines to generate electricity. Pumped hydro storage has the advantage of being a proven and scalable technology, though its implementation is geographically constrained due to the need for specific topographical conditions.
- **Compressed Air Energy Storage (CAES):** In CAES systems, excess energy is used to compress air and store it in underground caverns or other storage containers. When energy is required, the compressed air is released, heated, and used to

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drive turbines to generate electricity. CAES is particularly useful for long-duration energy storage but can be less efficient compared to other technologies due to energy losses during the compression and decompression processes.

- **Flywheels:** Flywheels store energy mechanically by rotating a mass at high speeds. When energy is needed, the rotational energy is converted back into electricity. Flywheels offer very fast response times and are useful for short-term stabilization of the grid, especially during rapid fluctuations in supply or demand. However, their energy storage capacity is limited compared to batteries or pumped hydro storage.

Each of these storage technologies offers unique benefits and limitations. The choice of which technology to use depends on the specific needs of the power grid, such as the required duration of energy storage, scalability, and geographic constraints.

2.2. Role of Energy Storage in Grid Stability

Energy storage systems play a crucial role in maintaining grid stability by addressing several key challenges associated with renewable energy integration. These include managing supply-demand imbalances, improving frequency regulation, and enhancing grid resilience.

- **Supply-Demand Balancing:** Energy storage systems help balance supply and demand by storing excess energy during periods of high generation (e.g., sunny or windy days) and releasing it when demand peaks or when renewable generation drops (e.g., at night or during calm weather). This capability smooths out the fluctuations in renewable energy generation

and ensures a continuous and reliable power supply to consumers.

- **Frequency Regulation:** The frequency of the electrical grid must remain stable within a narrow range (usually around 50 or 60 Hz). If generation exceeds demand or vice versa, the frequency can shift, leading to potential grid instability or even blackouts. Energy storage systems can rapidly inject or absorb energy to correct frequency imbalances, thus providing critical frequency regulation services to maintain grid stability.
- **Grid Resilience and Reliability:** Energy storage systems contribute to the overall resilience of the grid by providing backup power during outages or disturbances. This is particularly important as more distributed energy resources (DERs) are integrated into the grid. When there is a sudden loss of renewable generation or a fault in the system, energy storage can act as a buffer, ensuring that power remains available to critical infrastructure and preventing widespread disruptions.

2.3. Challenges in Integrating Energy Storage Systems

While energy storage systems offer significant potential for enhancing grid stability, their integration into existing grids presents several challenges.

- **Cost and Efficiency:** Although the cost of energy storage technologies, particularly batteries, has decreased significantly in recent years, they remain relatively expensive compared to traditional energy generation methods. The overall efficiency of storage systems, especially for long-duration storage, also

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varies, with some technologies experiencing energy losses during storage and retrieval processes.

- **Grid Compatibility and Infrastructure:** Integrating energy storage into existing grid infrastructure requires careful planning and system upgrades. The grid must be capable of handling the bidirectional flow of electricity between storage systems and the grid, which may necessitate the installation of new inverters, transformers, and control systems. Additionally, energy storage systems must be able to communicate seamlessly with other components of the grid to ensure that stored energy is dispatched at the right time and in the right amounts.
- **Regulatory and Market Barriers:** In many regions, regulatory frameworks and market structures are not fully equipped to accommodate large-scale energy storage. Policy reforms are needed to incentivize the deployment of energy storage systems, ensure fair compensation for grid services like frequency regulation and energy arbitrage, and create market mechanisms that recognize the value of storage in maintaining grid stability.

2.4. Future Trends in Energy Storage for Grid Stability

As the demand for renewable energy continues to grow, so too will the need for more advanced and efficient energy storage solutions. Ongoing research and development in the field of energy storage are focused on increasing the energy density, efficiency, and cost-effectiveness of storage technologies. For example, solid-state batteries and flow batteries are being explored as potential alternatives to conventional lithium-ion batteries, offering improved

performance and safety. Additionally, hybrid storage systems that combine different types of storage technologies (e.g., batteries with pumped hydro) may become more prevalent, optimizing the strengths of each technology.

Moreover, the advent of decentralized energy systems and the rise of microgrids will drive the need for more localized and flexible storage solutions. These systems, paired with advanced control algorithms and real-time data analytics, will allow for more efficient management of distributed energy resources and greater grid stability.

3. Advanced Control Systems for Renewable Energy Integration

The integration of renewable energy into existing power grids has introduced new complexities in grid management. Unlike traditional, centralized power plants, renewable sources such as wind and solar energy are distributed, intermittent, and subject to variable weather conditions. Consequently, power grids need to be more adaptable and responsive to the fluctuating availability of renewable energy. Advanced control systems play a crucial role in managing the dynamic behavior of renewable energy systems and ensuring their seamless integration into the grid. These systems enable real-time monitoring, optimization, and coordination of energy flows, thereby enhancing grid stability, reliability, and efficiency. This section explores the key components of advanced control systems, their significance in renewable energy integration, and the challenges associated with their implementation.

3.1. Key Components of Advanced Control Systems

Advanced control systems for renewable energy integration consist of several key components that work together to manage power flow,

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optimize system performance, and respond to fluctuations in renewable energy generation. These components include:

- **Power Management and Distribution Control:** Central to advanced control systems is the ability to manage and distribute power efficiently across the grid. This involves controlling the output from renewable energy sources, ensuring that energy generated by solar panels, wind turbines, and other distributed sources is effectively fed into the grid, and that power flows are balanced with demand. Control systems must continually adjust the operation of renewable energy plants to match the real-time energy requirements of the grid.
- **Energy Forecasting and Predictive Analytics:** To manage renewable energy integration effectively, control systems rely heavily on forecasting tools that predict the availability of renewable energy based on weather patterns, geographic data, and historical performance. Predictive analytics enable grid operators to anticipate fluctuations in renewable generation, such as sudden drops in solar power due to cloud cover or a lull in wind activity, and adjust the grid's operation accordingly.
- **Load and Demand Response Control:** An essential aspect of advanced control systems is their ability to manage load demand and enable demand-side management (DSM). By optimizing how energy is distributed across consumers, control systems can shift or reduce load during peak demand times, and coordinate with battery storage and other distributed resources. Demand response programs allow for dynamic pricing and incentivize consumers to reduce their energy

consumption when renewable generation is low or demand is high.

- **Grid Frequency and Voltage Regulation:** In a traditional grid, frequency and voltage regulation are critical for ensuring stable operation. However, the variable nature of renewable energy requires more advanced control techniques to maintain grid stability. Advanced control systems use algorithms that continuously monitor and adjust frequency and voltage levels to prevent imbalances that could result in equipment damage or blackouts. These systems help to stabilize the grid and maintain quality power even during rapid fluctuations in generation.

3.2. Real-Time Monitoring and Adaptive Control Techniques

One of the core features of advanced control systems is their ability to operate in real-time. Real-time monitoring allows grid operators to have a constant view of the grid's operational state, including the current level of renewable generation, energy storage, and demand. This information is processed and used to make instantaneous decisions about how to optimize power generation, distribution, and consumption.

- **Adaptive Control:** Adaptive control techniques allow the grid to automatically adjust its operation based on changing conditions. For example, when wind generation suddenly increases, the control system can rapidly adjust the operation of fossil fuel plants or energy storage systems to accommodate the surplus power. Conversely, when renewable generation falls, the system can ensure that backup generation sources are activated in a timely manner to avoid energy shortages.

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Adaptive control ensures that the grid is always operating at optimal efficiency, even in the face of changing generation patterns and demand fluctuations.

- **Model Predictive Control (MPC):** One of the most promising techniques in advanced grid control is Model Predictive Control, which uses mathematical models to predict future states of the grid based on current conditions. By forecasting power flows and system performance, MPC enables grid operators to make proactive adjustments before issues arise. This technique is particularly useful in mitigating the impacts of renewable energy variability, as it allows for more accurate scheduling and integration of diverse energy sources.
- **Decentralized and Distributed Control:** Given the increasing number of distributed energy resources (DERs), such as rooftop solar panels, battery storage, and electric vehicles, decentralized control systems are becoming more prevalent. These systems operate independently or in coordination with centralized control, allowing for faster decision-making and better responsiveness to local energy conditions. Distributed control systems also help prevent bottlenecks and failures caused by overloading in a single centralized controller, ensuring more robust and reliable grid operation.

3.3. The Role of Communication and IoT in Control Systems

The success of advanced control systems depends on reliable communication infrastructure and the effective use of real-time data. The Internet of Things (IoT) plays a significant role in enabling this communication, connecting renewable energy sources, energy storage units, smart meters, and other grid components to a central

control platform. Through IoT-enabled sensors and smart devices, control systems can collect vast amounts of real-time data on grid performance, renewable energy production, and consumption patterns.

- **Data Analytics and Cloud Computing:** The large volumes of data generated by IoT-enabled devices require sophisticated data analytics tools to extract actionable insights. Cloud computing platforms provide the scalability and processing power needed to analyze this data in real-time, allowing for rapid decision-making. Machine learning algorithms can also be used to identify trends, predict future energy usage patterns, and optimize control strategies, making the grid more responsive to changing conditions.
- **Communication Protocols:** Standardized communication protocols are essential for ensuring that all devices and systems in the grid can share information seamlessly. Protocols such as the OpenADR (Automated Demand Response) and the IEC 61850 for substation automation ensure that control systems can communicate effectively with DERs, energy storage systems, and other grid components. Robust communication networks are critical for maintaining the reliability and accuracy of control systems in the modern, decentralized grid.

3.4. Challenges and Future Developments in Control Systems

While advanced control systems have made significant progress in integrating renewable energy sources into the grid, several challenges remain. One of the main obstacles is the need for high-speed data processing and real-time decision-making. As renewable energy penetration increases, the frequency and scale of fluctuations in

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generation will become more pronounced, requiring control systems to adapt rapidly to avoid instability.

- **Cybersecurity Concerns:** As control systems become more interconnected and reliant on digital communication, the risk of cyberattacks also increases. Protecting critical grid infrastructure from malicious threats is a top priority, requiring robust cybersecurity measures and constant vigilance.
- **Integration of Emerging Technologies:** The integration of emerging technologies, such as blockchain for energy transactions and artificial intelligence for system optimization, will further enhance control systems' capabilities. These technologies can improve transparency, security, and efficiency, allowing for smarter, more autonomous grid management.
- **Scalability and Interoperability:** As grids become more complex and decentralized, ensuring that control systems can scale and work across diverse regions and technologies is essential. Interoperability between different devices, systems, and regions will be crucial to managing the global transition to renewable energy and ensuring a stable, integrated grid.

Advanced control systems are fundamental to the successful integration of renewable energy into the power grid. By employing real-time monitoring, adaptive control techniques, and leveraging IoT and data analytics, these systems help optimize energy flow, stabilize grid operations, and ensure reliability. As renewable energy continues to play an increasingly dominant role in global energy systems, the continued evolution of control technologies will be essential for meeting the challenges of a sustainable and resilient energy future.

4. Power System Protection in Renewable Energy Networks

The integration of renewable energy sources into power grids presents new challenges for power system protection. Traditional protection schemes were designed primarily for centralized, fossil-fuel-based generation, where power flows were predictable and linear. However, renewable energy sources such as solar, wind, and hydropower are often decentralized, variable, and can be interconnected to the grid at multiple points. This introduces complexities in fault detection, isolation, and recovery. The dynamic nature of renewable energy systems requires advanced protection strategies that can adapt to changing conditions and ensure the stability and reliability of the grid. This section explores the importance of power system protection in renewable energy networks, the challenges associated with their integration, and the evolving techniques used to address these challenges.

4.1. The Role of Protection Systems in Renewable Energy Integration

Power system protection is designed to detect and isolate faults in the grid to prevent damage to equipment, minimize the risk of widespread outages, and ensure the safety of personnel and consumers. In renewable energy networks, protection systems are particularly critical because of the following reasons:

- **Distributed Generation and Fault Locations:** Unlike traditional centralized power plants, renewable energy systems are often distributed across wide geographical areas, creating numerous points of potential faults. Distributed generation, including rooftop solar panels, small wind turbines, and energy storage systems, increases the complexity of fault detection and

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isolation. Protection systems must be able to accurately locate faults and take corrective action quickly, regardless of where they occur within the network.

- **Intermittent and Variable Generation:** The output from renewable energy sources is not constant. For instance, solar energy depends on sunlight, and wind energy fluctuates based on wind speed. This variability can lead to sudden surges or drops in power generation, which may pose risks to grid stability and protection systems. A reliable protection system must account for these fluctuations and ensure that protection mechanisms do not falsely trigger during normal operation or fail during faults.
- **Reverse Power Flow:** In traditional power grids, power flows in one direction—from large, centralized power plants to end-users. However, in renewable energy networks, power can flow in multiple directions due to the decentralized nature of generation. For example, in the case of excess generation from rooftop solar panels, electricity can flow back into the grid. Protection systems must be capable of detecting and managing reverse power flow, as traditional protection mechanisms may not have been designed to handle such scenarios.

4.2. Fault Detection and Isolation in Renewable Energy Networks

One of the primary functions of power system protection is to detect faults (such as short circuits or equipment malfunctions) and isolate the affected portion of the network to prevent further damage. In renewable energy networks, fault detection and isolation are more challenging due to the following factors:

- **High Impedance Faults:** Renewable energy networks, especially those involving distributed generation, are often exposed to high-impedance faults, such as those caused by damaged power lines or faulty connections. These faults are harder to detect because they do not result in large current spikes like low-impedance faults. Advanced fault detection methods, such as voltage-based or signal-processing techniques, are required to detect high-impedance faults quickly and accurately in these environments.
- **Protection Coordination:** With renewable energy networks, multiple generation sources can be connected to the grid at various locations. Protection systems must coordinate the actions of protective relays to ensure that only the affected part of the network is disconnected, without compromising the stability of the entire grid. Protection coordination is essential to prevent unnecessary disconnections, which could lead to cascading outages, especially in systems with high renewable penetration.
- **Advanced Fault Detection Algorithms:** Modern protection systems rely on advanced algorithms, such as artificial intelligence (AI) and machine learning, to improve the accuracy and speed of fault detection. These algorithms can analyze real-time data from the grid to identify fault conditions and predict potential issues before they lead to system failures. For instance, AI-powered protection schemes can learn from historical fault data and adapt their detection strategies to improve fault location accuracy and minimize response times.

4.3. Protection Challenges in Microgrids and Hybrid Systems

Microgrids and hybrid renewable energy systems, which combine different types of renewable generation with energy storage, are becoming more common as part of the push for decentralized energy solutions. These systems introduce additional protection challenges:

- **Island Mode Operation:** Microgrids are capable of operating independently (in island mode) when disconnected from the main grid. In island mode, the protection system must handle all faults locally, ensuring that the microgrid remains stable and operational despite any faults. The challenge lies in designing protection schemes that can seamlessly switch between grid-connected and islanded operation, without risking equipment damage or loss of service.
- **Multiple Protection Schemes:** Hybrid systems, which may include wind, solar, and storage technologies, require multiple protection schemes to cater to the specific characteristics of each type of generation. For example, protection systems for wind turbines need to account for the possibility of blade damage or mechanical failure, while solar power systems require protection against inverter faults or panel malfunctions. The combination of various protection schemes in hybrid systems increases the complexity of system design, but is necessary for ensuring comprehensive protection across the entire network.
- **Dynamic Grid Configurations:** The configuration of a grid may change rapidly, especially with the increasing penetration of distributed renewable resources and the deployment of flexible energy storage. Protection systems must be designed to

accommodate these changes dynamically, ensuring that protection strategies are updated in real time to reflect new grid configurations.

4.4. Advanced Protection Technologies for Renewable Energy Networks

To address the challenges posed by renewable energy integration, several advanced protection technologies have been developed to enhance the reliability, speed, and accuracy of fault detection and isolation in renewable energy networks:

- **Digital Relays and Intelligent Electronic Devices (IEDs):** Modern protection systems often utilize digital relays and IEDs, which offer more flexibility and higher precision compared to traditional electromechanical relays. These devices can be programmed with sophisticated algorithms to detect faults, measure system parameters, and make real-time decisions. Digital relays enable faster fault detection and the ability to perform more complex protection functions, such as adaptive protection and self-healing capabilities.
- **Phasor Measurement Units (PMUs):** PMUs are devices that provide real-time, synchronized measurements of voltage and current across the power grid. These measurements are crucial for understanding the dynamics of the grid and detecting faults or disturbances. PMUs are particularly useful in wide-area monitoring and protection, allowing for better coordination and faster fault detection in renewable energy networks, where power flows may be less predictable.

- **Adaptive Protection:** Adaptive protection systems are able to modify their protection settings based on real-time operating conditions. This flexibility allows for more efficient protection in grids with high renewable penetration, where operating conditions (such as generation levels and load profiles) are constantly changing. Adaptive protection schemes can be adjusted dynamically, improving fault detection accuracy and minimizing unnecessary disconnects.
- **Wide-Area Protection Systems:** Wide-area protection schemes use data from multiple sensors across the grid to provide a comprehensive view of the entire network. These systems can detect system-wide disturbances and respond more effectively to faults that could have widespread consequences, such as cascading outages. Wide-area protection is particularly useful in large renewable energy networks, where power generation is distributed and fault events can have complex, far-reaching impacts.

4.5. Future Trends in Power System Protection for Renewable Energy

As renewable energy adoption continues to grow, power system protection strategies will need to evolve to meet new challenges. Future trends in protection technologies for renewable energy networks include:

- **Increased Use of Artificial Intelligence and Machine Learning:** AI and machine learning will continue to play a significant role in enhancing fault detection, prediction, and protection coordination. These technologies can analyze vast amounts of real-time data and improve system reliability by

detecting potential failures before they occur and optimizing protection strategies for changing grid conditions.

- **Integration of Energy Storage into Protection Systems:** As energy storage systems become more widespread, their role in power system protection will become increasingly important. Storage systems can provide fast-acting backup power during faults, supporting the grid during periods of instability. Protection schemes will need to account for the presence of storage systems, coordinating their operation with renewable generation to ensure grid reliability.
- **Enhanced Grid Resilience through Self-Healing Systems:** The concept of self-healing grids, which can automatically detect faults and restore service without human intervention, will become more prevalent. These systems will rely on advanced protection and control technologies to minimize downtime and quickly restore power after disturbances.

The power system protection in renewable energy networks requires innovative solutions to address the unique challenges posed by decentralized, intermittent, and variable generation sources. Advanced protection technologies, such as digital relays, adaptive protection schemes, and wide-area monitoring systems, are essential for ensuring grid stability, minimizing faults, and preventing widespread outages. As renewable energy continues to transform the global power grid, the development of smarter and more resilient protection systems will be crucial to the safe and reliable operation of the energy infrastructure.

5. Summary

The integration of renewable energy into the power grid presents new challenges that require innovative solutions to ensure grid stability, reliability, and protection. Energy storage solutions play a crucial role in stabilizing the grid by storing excess renewable energy and providing backup during periods of low generation. Advanced control systems, leveraging real-time data and predictive algorithms, optimize power distribution, enhance system responsiveness, and facilitate the seamless integration of variable renewable sources. Additionally, power system protection strategies have evolved to address the complexities of distributed generation, intermittent energy production, and reverse power flow, ensuring that faults are quickly detected and isolated to prevent widespread outages. Together, these technologies work to create a more resilient, efficient, and secure energy grid capable of supporting the increasing role of renewables in global energy systems.

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