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Investigating Control Strategies for Optimizing the Performance of Wind Turbines, Solar Panels, and Energy Storage Systems

Deesani Dutta

Maulana Abul Kalam Azad University of Technology
Email : ddutta2210@gmail.com

ABSTRACT:

The transition to renewable energy sources is a vital step towards addressing climate change and achieving a sustainable energy future. Wind turbines, solar panels, and energy storage systems play pivotal roles in this transition, but their efficient operation and performance optimization are essential to ensure the reliable supply of clean energy. This research investigates various control strategies aimed at maximizing the efficiency and performance of these renewable energy technologies.

The study begins by examining control algorithms for wind turbines, focusing on pitch control, yaw control, and power control techniques. These strategies aim to enhance energy capture, minimize mechanical stress, and ensure safe operation under various wind conditions. Simultaneously, the research delves into control mechanisms for solar panels, including maximum power point tracking (MPPT) algorithms, which optimize the electrical output by dynamically adjusting the panel's operating conditions according to solar irradiance and temperature.

In addition, the research explores advanced control strategies for energy storage systems, such as battery management systems (BMS). These BMS solutions incorporate state-of-charge (SoC), state-of-health (SoH), and state-of-power (SoP) control to enhance the overall performance, lifespan, and safety of energy storage systems. They also enable integration with renewable energy sources for grid stability and load balancing.

Furthermore, the investigation takes into consideration the integration of these control strategies for a holistic approach to renewable energy systems. Synergistic control between wind turbines, solar panels, and energy storage systems is explored to optimize the overall energy output and improve the reliability of renewable energy generation. This research combines theoretical analysis, simulation studies, and experimental validation to assess the effectiveness of these control strategies in real-world applications.

The findings of this research have significant implications for the renewable energy sector, offering insights into the enhancement of energy production and grid integration. By optimizing the performance of wind turbines, solar panels, and energy storage systems through advanced control strategies, this study contributes to the acceleration of the global transition to sustainable and clean energy sources.

1. Introduction:

Investigating control strategies for optimizing the performance of renewable energy systems, including wind turbines, solar panels, and energy storage systems, is crucial for advancing the efficiency and sustainability of modern energy production. With the growing emphasis on clean energy solutions, understanding how to maximize the output and reliability of these technologies has become a pivotal focus in the field of renewable energy research.

In this pursuit, researchers and engineers delve into various control strategies that aim to enhance the overall performance of these renewable energy systems. Through advanced monitoring, data analysis, and sophisticated control algorithms, these strategies seek to optimize power generation, improve grid integration, and ensure seamless energy supply.

Efforts are underway to develop adaptive control mechanisms that can dynamically adjust to changing environmental conditions, such as varying wind speeds, solar irradiance, and energy demand fluctuations. By implementing intelligent control techniques, the aim is to strike a balance between energy production and consumption, thereby fostering a more stable and sustainable energy ecosystem.

This investigation not only contributes to the advancement of renewable energy technology but also addresses the challenges associated with grid stability and energy management. By harnessing the potential of these control strategies, it is possible to pave the way for a more resilient and efficient renewable energy infrastructure, ultimately fostering a cleaner and more sustainable energy future.

Provide an overview of renewable energy sources, including wind turbines and solar panels.

Renewable energy sources play a vital role in addressing the global energy challenge while mitigating the impact of climate change. Wind turbines and solar panels, in particular, have gained significant attention as sustainable alternatives to traditional fossil fuel-based energy generation.

Overview of these two key renewable energy sources:

1. Wind Turbines:

Wind energy is harnessed through the use of wind turbines, which convert the kinetic energy of the wind into electrical power. The main components of a wind turbine include the rotor, generator, and tower. As the wind blows, it causes the blades of the rotor to rotate, thereby driving the generator to produce electricity. Wind turbines can be deployed both onshore and offshore, with advancements in technology allowing for larger and more efficient turbines that can capture energy from varying wind speeds. Large-scale wind farms have become increasingly common, contributing significantly to electricity generation in many parts of the world.

2. Solar Panels:

Solar energy is derived from the sun's radiation and is captured through photovoltaic (PV) panels or solar thermal systems. Photovoltaic panels convert sunlight directly into electricity, while solar thermal systems use sunlight to heat a fluid that produces steam to drive a turbine connected to a generator. Solar panels are typically installed on rooftops or in large solar farms, utilizing the abundance of sunlight to generate clean, renewable energy. Advances in solar technology have led to increased efficiency, reduced costs, and the development of innovative solutions such as building-integrated photovoltaics (BIPV) and concentrated solar power (CSP) systems.

These renewable energy sources offer several advantages, including reduced greenhouse gas emissions, energy independence, and the potential for decentralized energy production. However, challenges remain, such as intermittency (in the case of solar and wind), grid integration, and the need for efficient energy storage solutions to ensure reliable power supply. Overcoming these challenges requires continued research and development, along with effective policy measures to promote the widespread adoption of renewable energy technologies, thereby fostering a sustainable and environmentally friendly energy future.

Optimizing the performance of renewable energy sources:

Optimizing the performance of renewable energy sources, such as wind turbines and solar panels, is critical for several reasons, reflecting the broader goals of sustainability, energy security, and environmental protection. Here are some key points highlighting the significance of this optimization:

1. Increased Energy Efficiency: Efficient operation of renewable energy sources ensures higher energy yields per unit area, thereby maximizing the generation potential. This leads to more cost-effective energy production and a reduction in the overall cost per unit of electricity, making renewable energy more competitive with traditional fossil fuels.

2. Enhanced Reliability and Stability: Optimized performance enhances the reliability and stability of the power grid by providing a more predictable and consistent energy supply. This is essential for ensuring a smooth transition from traditional energy sources to renewable ones, as well as for maintaining grid stability in the face of fluctuating energy inputs.

3. Mitigation of Environmental Impact: By maximizing the energy output of renewable sources, the need for non-renewable energy generation is reduced, resulting in a corresponding decrease in greenhouse gas emissions and other pollutants. This contributes significantly to efforts aimed at mitigating climate change and reducing the overall environmental footprint of energy production.

4. Energy Security and Independence: Increasing the efficiency of renewable energy sources lessens dependence on fossil fuels and foreign energy sources, thereby enhancing energy security for nations. By harnessing local renewable resources more effectively, countries can reduce their vulnerability to energy supply disruptions and geopolitical uncertainties associated with traditional energy imports.

5. Technological Advancement and Innovation: The drive to optimize performance stimulates innovation in the renewable energy sector, leading to the development of more efficient and cost-effective technologies. This, in turn, fosters economic growth, job creation, and the establishment of a robust renewable energy industry, driving forward a sustainable and resilient energy future.

6. Community and Economic Benefits: Improved performance of renewable energy sources can bring economic benefits to local communities through job creation, investments in infrastructure, and increased tax revenues. Additionally, the establishment of renewable energy facilities can provide communities with a more stable and affordable energy supply, enhancing overall quality of life.

2. Objectives of the research:

The objectives of utilizing renewable energy sources such as wind turbines are multifaceted and reflect the broader goals of transitioning towards a more sustainable and environmentally friendly energy system. Here are some key objectives:

1. Wind turbines aim to generate electricity without relying on fossil fuels. By doing so, they help reduce greenhouse gas emissions, which contribute to climate change. This objective aligns with global efforts to mitigate the impacts of climate change.
2. Wind energy reduces dependence on fossil fuel imports and enhances a nation's energy security. It minimizes exposure to volatile energy prices and supply disruptions associated with conventional energy sources.

3. Wind turbines are a key component of a diversified energy portfolio. They complement other renewable energy sources like solar and hydropower, reducing the risk associated with over-reliance on a single energy source.
4. Wind turbines generate electricity without emitting air pollutants or greenhouse gases. This helps improve air quality and reduces health risks associated with air pollution.
5. The wind energy sector provides jobs in manufacturing, construction, and operations. Additionally, it can stimulate local economies through investments in wind farm projects.
6. Many wind farms are located in rural areas, providing economic opportunities for these regions. They can generate income for landowners and increase tax revenue for local communities.
7. Wind energy can contribute to stabilizing and even reducing electricity costs for consumers, as it often displaces more expensive fossil fuel-based electricity generation.
8. Wind turbines can be deployed in remote or off-grid areas, providing access to electricity in regions without traditional power infrastructure.
9. Research and development in wind energy technology can lead to innovations that improve efficiency, reduce costs, and make wind power more accessible.
10. Wind energy can enhance grid stability when combined with energy storage systems and smart grid technologies. It can also reduce the need for peak-load power plants, thus contributing to grid reliability.
11. Compared to many conventional energy sources, wind turbines have a lower environmental impact in terms of water usage and land footprint.
12. As a virtually inexhaustible energy source, wind energy contributes to long-term energy security by reducing the reliance on finite fossil fuels.

3. Importance of control strategies in maximizing energy production:

Control strategies play a pivotal role in maximizing energy production and efficiency across various sectors, including renewable energy, traditional power generation, and industrial processes. Their importance lies in their ability to optimize operations, enhance system performance, and improve overall energy utilization. Some key aspects highlighting the importance of control strategies in this context include:

1. Control strategies enable the efficient utilization of energy resources by regulating and optimizing energy conversion processes, reducing energy wastage, and minimizing unnecessary energy consumption.
2. In the context of renewable energy sources, effective control strategies help in maximizing energy production from sources like solar, wind, and hydro by ensuring that these systems operate at their peak efficiency levels and adapt to varying environmental conditions.
3. Control strategies are crucial in maintaining the stability and reliability of power grids by managing the balance between electricity demand and supply, regulating voltage levels, and controlling the frequency of the grid.
4. Control strategies contribute to improving the efficiency of industrial processes by regulating parameters such as temperature, pressure, and flow rates, thereby reducing energy consumption and optimizing production output.
5. Implementing effective control strategies can lead to cost savings by minimizing energy waste, improving process efficiency, and reducing the need for unnecessary energy consumption, ultimately resulting in lower operational costs.
6. By optimizing energy production and consumption, control strategies contribute to reducing the environmental impact of energy-related activities, promoting sustainable practices, and mitigating the carbon footprint associated with energy generation.

4. Methodology:

4.1 Implementation and Validation of Generic Wind Turbine Model

To validate the implemented model, the model to field measurement validation method is employed. The “play-back” approach and the measurement data from Siemens Wind Power are used. The results show that there is a good agreement between the simulation results and the measurements. The errors between the simulation results and measurements are calculated according to the voltage dip windows and the index definition specified in the IEC 61400-27-1 committee draft.

4.2 Model description

The configuration of Type 1 WTG has been described and not repeated. One thing to be noticed is that the blade pitch angles of the Type 1 WTG can either be fixed or controllable. The latter one is used for Fault-Ride through (FRT) control. In the initial IEC committee draft, Type 1 WTGs are accordingly divided into two subgroups:

- Type 1A: without FRT control.
- Type 1B: with blade angle FRT control.

The Type 1B model is removed from the newly modified IEC committee draft.

However, it is also studied in this thesis.

4.2.1 Structure of generic Type 1A WTG model

The structure of the generic Type 1A WTG model is illustrated in Fig. 4.1, which is comprised of aerodynamic, mechanical, generator system, electrical equipment and grid protection blocks.

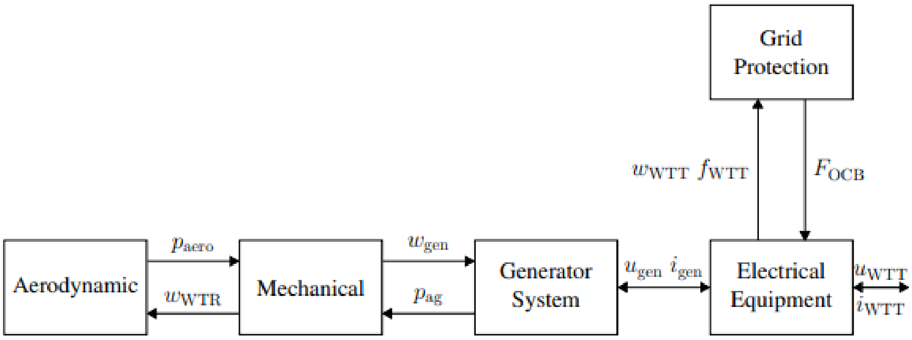

Figure 4.1: Runtime WTG model structure of Type 1A

4.2.1.1 Aerodynamic block

The aerodynamic torque is considered to be constant during the short time period. Therefore, constant aerodynamic torque model is used instead of pseudo governor model described in [117]. The model parameters are given in Table 4.1 and the runtime block diagram is given in Fig. 4.2.

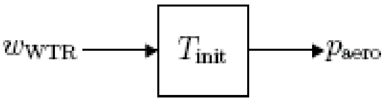

Figure 4.2: Block diagram for constant aerodynamic torque model

4.2.1.2. Mechanical block

The mechanical part is implemented by a two-mass model which represents the low-speed turbine rotor and the high-speed generator, respectively. The connecting resilient shaft is modeled as a spring and a damper. The block diagram of IEC standard model is shown in Fig. 4.3. The parameters of the two-mass block are listed in Table 4.2.

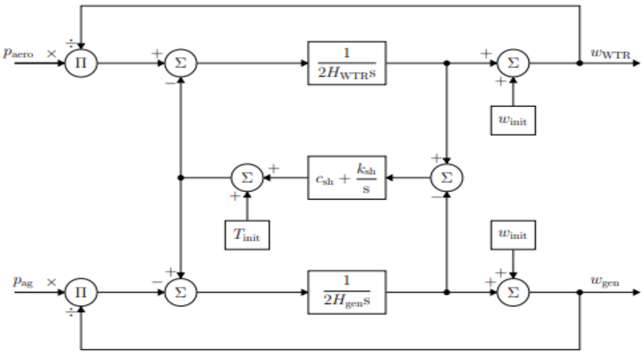

Figure 4.3: Block diagram for two-mass model in IEC standard

4.2.1.3 Wind speed estimation

In this part, the estimation accuracy of wind speed is tested. The wind profile applied has average wind speed of 7 m/s and turbulence intensity is 0.15, derived by using the Von Karman spectrum in the IEC standard. The variation covers the most range of partial load regime−between 5 m/s and 11 m/s. The wind speed is estimated by means of the method described in Section 5.2.1. The comparison between actual and estimated wind speed is depicted in Fig. 5.10. It can be observed that there is a good match between both curves. The standard deviation is 0.0657 m/s.

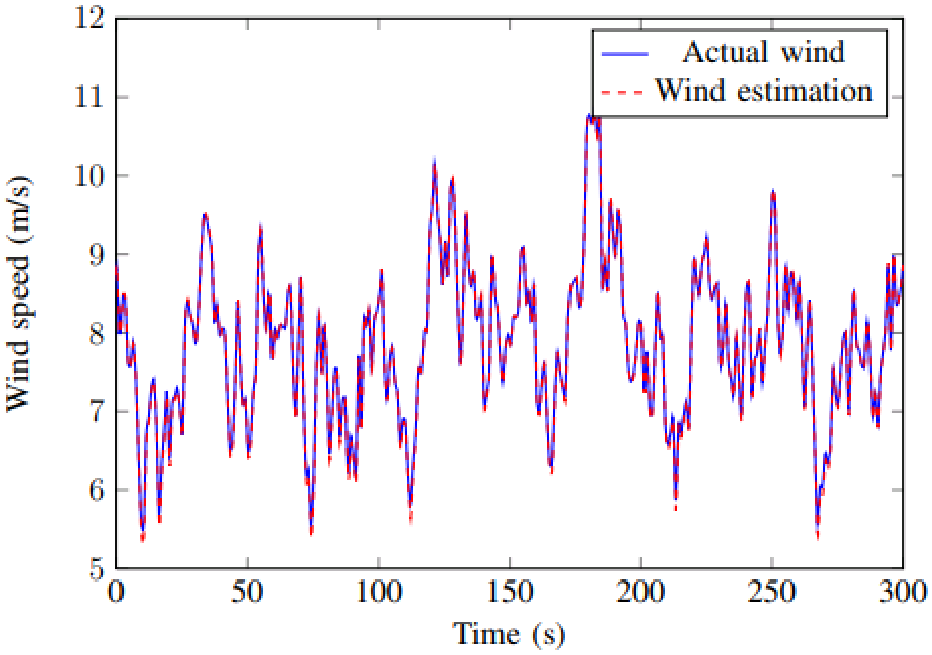

Figure 4.4 Comparison of actual wind and wind estimation

Tracking performance with wind speed variation Based on the estimated wind speed, the tracking performance of the speed reference ω ref g is the key factor which determines the power efficiency and production. This case study is divided into two scenarios based on the different turbulence intensities of wind profiles: Scenario 1 and Scenario 2, depicted in Fig. 5.11 (a).

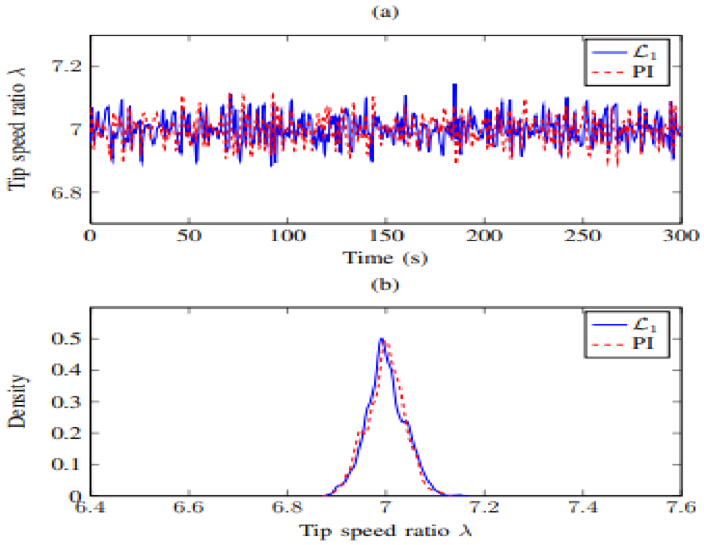

Figure 5.12: Comparison of λ variation during the operation in Scenario 1: (a) in time series format; (b) λ in density format.

4.2.1.4 Wind turbine generator technology

The present WTG based WECS can be generally divided into the following four types .

Type 1

This type represents the wind turbine with directly gird connected Induction Generator (IG) with fixed rotor resistance (typically Squirrel Cage Induction Generator (SCIG)). As illustrated in Fig. 2.1, the Wind Turbine Rotor (WTR) is connected to the IG via a Gearbox (GB). The capacitor bank provides reactive power compensation. Most Type 1 WTGs are equipped with Mechanically Switched Capacitor (MSC) banks. As the protection device, the main Circuit Breaker (CB) disconnects generator and capacitor from the grid during the fault.

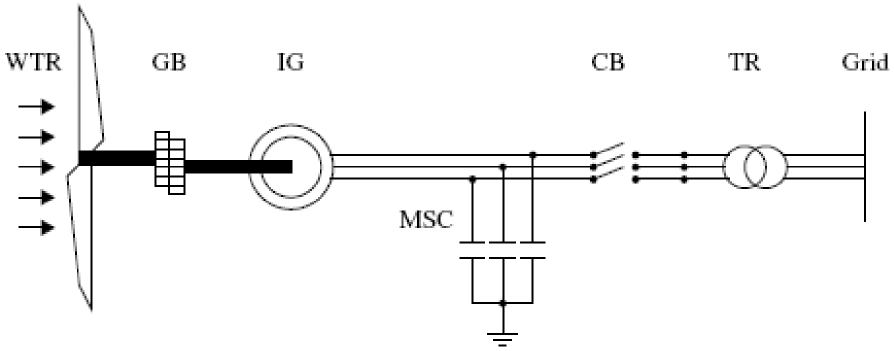

Figure 2.1: General structure of Type 1 WTG

Type 2

This type represents the wind turbine with directly grid connected IG with Variable Rotor Resistance (VRR). The general structure of Type 2 WTG is illustrated in Fig. 2.2. As an evolution of Type 1 WTG, the total (internal plus external) rotor resistance is adjustable by regulation of power electronics. In such way, the slip of the generator can be controlled which affects the slope of the mechanical characteristic. The range of the dynamic speed control is determined by how large the additional resistance is. Usually the control range is up to 10% over the synchronous speed.

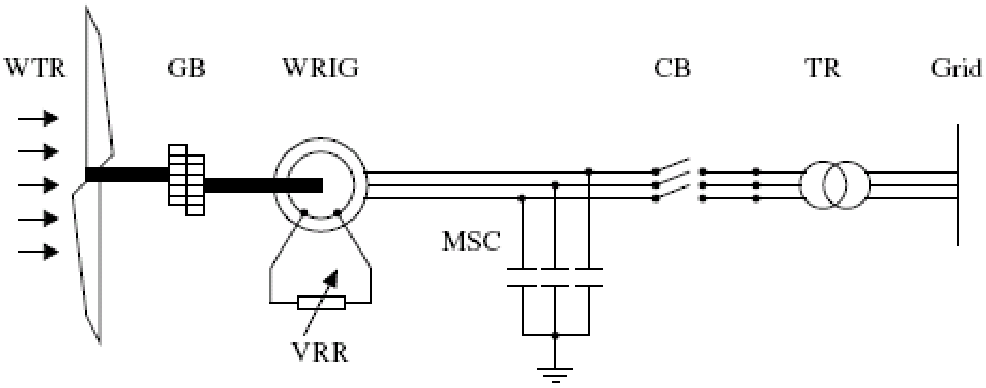

Figure 2.2: General structure of Type 2 WTG

Type 3

This type represents the wind turbine with Double-Fed Induction Generator (DFIG). As illustrated in Fig. 2.3, the DFIG is a WRIG with the stator windings connected directly to the three-phase, constant frequency grid and the rotor windings connected to a back-to-back VSCs□Rotor Side Converter (RSC) and Grid Side Converter (GSC) [21]. They are decoupled with a Direct Current (DC) link. The main idea is that the RSC controls the generator in terms of active and reactive power, while the GSC controls the DC-link voltage and ensures operation at a large power factor. 1

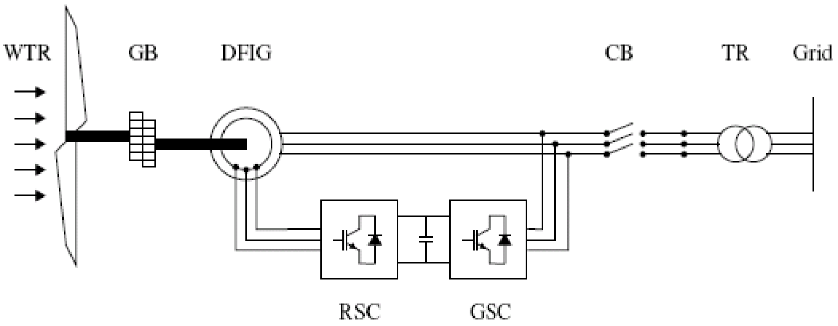

Figure 2.3: General structure of Type 3 WTG

4.2 Describe the research design and approach.

The research design and approach for wind turbines, solar panels, and energy storage systems typically involve a combination of scientific and engineering methodologies. Researchers focus on improving the efficiency, reliability, and sustainability of these renewable energy technologies. Here's a general overview of the research design and approach for each:

1. Wind Turbines:

Research Design:

1. Wind resource assessment: Researchers study local wind patterns to determine suitable locations for wind farms.
2. Aerodynamic design: Computational simulations and wind tunnel testing are used to optimize the blade design for maximum energy capture.
3. Structural design: Researchers work on designing robust structures to withstand harsh environmental conditions.
4. Generator and power electronics: Research focuses on developing more efficient generators and power conversion systems.
5. Grid integration: Researchers work on integrating wind farms into the power grid while maintaining grid stability.

Research Approach:

1. Theoretical modeling: Mathematical models are used to predict the performance of wind turbines.
2. Experimental testing: Full-scale wind turbines are tested in various environmental conditions to validate their performance.

3. Data analysis: Collected data from operating wind farms is analyzed to improve turbine designs.
4. Material science: Research is conducted to develop lighter and more durable materials for turbine components.
5. Collaboration: Wind turbine research often involves collaboration between engineers, meteorologists, and environmental scientists.

2. Solar Panels:

Research Design:

1. Solar cell technology: Researchers explore different types of photovoltaic cells (e.g., silicon, thin-film, perovskite) to improve efficiency and reduce costs.
2. Manufacturing processes: Optimization of manufacturing techniques to increase production efficiency and reduce waste.
3. Bifacial panels: Research on the design and performance of panels that can capture sunlight from both sides.
4. Energy yield prediction: Modeling software to estimate energy production in different locations and conditions.
5. Integration with building materials: Development of solar-integrated roofing and façade materials.

Research Approach:

1. Materials research: Developing new materials and coatings to enhance light absorption and durability.
2. Testing and characterization: Measuring the efficiency and durability of solar panels under various conditions.
3. Field trials: Deploying panels in real-world environments and monitoring performance.
4. Cost reduction analysis: Identifying ways to reduce manufacturing costs and improve economies of scale.
5. Collaboration: Collaboration with materials scientists, electrical engineers, and industry partners is common.

3. Energy Storage Systems:

Research Design:

1. Battery chemistry: Research on different battery chemistries, such as lithium-ion, solid-state, and flow batteries.
2. Energy density improvement: Efforts to increase energy storage capacity and reduce size and weight.
3. Safety and longevity: Research on developing batteries with longer lifespans and improved safety features.
4. Grid integration: Designing systems that can store and discharge energy efficiently into the power grid.
5. Second-life batteries: Exploring the use of retired electric vehicle batteries for stationary energy storage.

Research Approach:

1. Laboratory testing: Testing battery prototypes in controlled environments to assess their performance and safety.
2. Field trials: Installing energy storage systems in real-world settings to gather data on their effectiveness.
3. Simulation modeling: Developing computer models to simulate battery behavior under various conditions.
4. Materials research: Investigating new materials for electrodes, electrolytes, and casings.
5. Collaboration: Collaborating with electrical engineers, chemists, and grid operators for comprehensive research.

4.3 Explain the data collection methods, including sensors and data acquisition systems.

Data collection methods for wind turbines, solar panels, and energy storage systems play a critical role in monitoring and optimizing their performance. These methods typically involve the use of various sensors and data acquisition systems. Here's an overview of how data is collected for each of these renewable energy systems:

1. Wind Turbines:

1. **Anemometers:** Anemometers are sensors that measure wind speed. Cup anemometers and sonic anemometers are commonly used in wind turbines to determine the speed and direction of the wind. This data is crucial for understanding the available wind resource.
2. **Wind Vanes:** Wind vanes or wind direction sensors provide information about the wind's direction. This information is used to ensure that the turbine is optimally oriented into the wind.

3. **Rotor Speed Sensors:** Sensors are installed on the turbine's rotor or blades to measure their rotational speed. This data is essential for controlling the turbine's output and safety.
4. **Turbine Temperature Sensors:** Temperature sensors monitor the temperature of various components within the turbine, such as the gearbox and generator. Overheating can indicate potential issues.
5. **Vibration Sensors:** Vibration sensors are used to monitor mechanical vibrations in the turbine. High vibrations can indicate problems in the gearbox or other components.
6. **Control Systems:** Wind turbines are equipped with control systems that collect and process data from various sensors to adjust the turbine's pitch, yaw, and other parameters for optimal performance.

2. Solar Panels (Photovoltaic Systems):

1. **Solar Irradiance Sensors:** Pyranometers and photodiode sensors measure solar irradiance, which is the amount of sunlight incident on the solar panels. This data helps determine the energy potential of the panels.
2. **Temperature Sensors**: Temperature sensors are often placed on or near the solar panels to monitor their temperature. High temperatures can affect the efficiency of solar cells.
3. **Current and Voltage Sensors:** Current and voltage sensors are used to monitor the electrical output of the solar panels, helping track their performance and power production.
4. **Inverters:** Solar panel systems typically have inverters that convert the direct current (DC) generated by the panels into alternating current (AC) for use in buildings or the grid. Inverters often have monitoring systems that collect data on power output.

3. Energy Storage Systems:

1. **Battery Management Systems (BMS):** Energy storage systems, like lithium-ion batteries, have built-in BMS that monitor the state of charge, state of health, and temperature of individual battery cells. BMS units collect and process this data to optimize battery performance and ensure safety.
2. **Current and Voltage Sensors**: Sensors are used to monitor the current and voltage of the energy storage system. This information is crucial for charge and discharge control.
3. **Environmental Sensors:** Environmental sensors may be used to monitor the temperature and humidity in the vicinity of the energy storage system, as these factors can affect battery performance.
4. **Data Loggers and Supervisory Control Systems:** Data loggers and control systems collect, store, and analyze data from various sensors. They may also interface with the grid and renewable energy sources to manage energy flow and storage.

5. Results:

Optimizing the performance of renewable energy systems like wind turbines, solar panels, and energy storage systems is crucial for maximizing their efficiency and economic viability. However, there are several unexpected findings and challenges that engineers and researchers have encountered in this process. Here are some of them:

1. Environmental Factors:

1. Wind Turbines: Wind patterns can be highly variable and unpredictable. Turbulence, wind shear, and wind direction changes can affect turbine performance. Site-specific factors, like local terrain and nearby structures, can create unexpected turbulence, reducing energy production.
2. Solar Panels: Dust, dirt, and shading issues can significantly impact solar panel efficiency. Even small amounts of shading on a solar panel can lead to substantial power loss. Moreover, extreme weather events, like hail or heavy snow, can damage solar panels.

2. Component Degradation:

1. All Renewable Systems: Over time, components degrade, which can lead to a decrease in performance. For example, turbine blades can erode, and solar panels can degrade due to exposure to UV radiation. Battery storage systems may suffer from capacity fade and decreased performance as they age.

3. Grid Integration:

1. Intermittency: The variable nature of renewable energy sources can be challenging to integrate into the grid. Unexpected fluctuations in power output from wind or solar sources can strain grid stability, requiring advanced grid management solutions.

2. Grid Compatibility: In some cases, the existing grid infrastructure may not be well-suited for the integration of renewable energy systems. Upgrading the grid can be costly and logistically challenging.

4. Energy Storage:

1. Battery Degradation: Energy storage systems, particularly lithium-ion batteries, can experience unexpected degradation due to temperature fluctuations and cycling. This can affect their capacity and overall performance.
2. Material Scarcity: The manufacturing of energy storage systems relies on specific materials like lithium and cobalt. The availability and ethical sourcing of these materials can pose unexpected challenges for the industry.

5. Cost vs. Performance:

1. Balancing cost-effectiveness with performance is an ongoing challenge. As technology advances, system costs can decrease, but there's a constant need to ensure that performance improvements align with economic feasibility.

6. Regulatory and Policy Hurdles:

1. Policies and regulations can significantly impact the adoption and performance of renewable energy systems. Uncertain or unfavorable policies, such as reductions in government incentives or net metering changes, can disrupt project economics.

7. Human and Wildlife Interactions:

1. Wind Turbines: Unexpected bird and bat fatalities due to collisions with turbine blades have raised environmental concerns and may necessitate mitigation efforts.
2. Solar Panels: Glare issues from solar installations can disturb nearby residents and wildlife, requiring consideration during design and installation.

8. Novel Technologies:

1. Innovative technologies may present unexpected challenges and unknown variables. For example, emerging solar panel designs or next-generation energy storage materials may encounter unforeseen obstacles during development and deployment.

6. Conclusion:

It is concluded that the 6-blade turbines output greater power than the corresponding counterparts. The power output data were then produced with each blade number scenario under incremental power supply varied from 6V to 12V. The energy balance of wind energy is very positive. The energy consumed in the whole chain of wind plants is recovered in several average operational months. Wind turbines use blades to collect the wind's kinetic energy. Wind flows over the blades creating lift (similar to the effect on airplane wings), which causes the blades to turn. The blades are connected to a drive shaft that turns an electric generator, which produces (generates) electricity. Wind turbines harness the wind a clean, free, and widely available renewable energy source—to generate electric power. The control strategies of providing inertial response and primary frequency control from wind power can either be implemented at the local wind turbine control level or the wind power plant control level. From the control point of view, the latter one seems to be the most robust and consistent solution. To perform active power control, the reloading control is proposed, either through pitch angle adjustment or increasing rotor speed. Besides, the other aspects including the overproduction for inertial control, recovery strategy after frequency restoration are reviewed.

The secondary frequency control, also called AGC or LFC, is the centralized automatic control to restore the frequency and power interchanges. Several new AGC algorithms are presented which use LQR, MPC, AI, etc. They can deal 32 Roles of Wind Power Plants in Modern Power Systems with the uncertainty and variability of wind power more efficiently. For a wind power plant itself, it is also desirable to make the wind power plant operate as a conventional power plant.

Control system is essential in the wind-BESS system due to the high-cost value of the BESS. In this paper, several control strategies used to smooth the wind power output with an optimal battery energy storage system were discussed.

The control technologies are classified into three main categories: wind-power filtering, the BESS charge/discharge dispatch, and optimization with wind-speed prediction. The major filters are low-pass, high-pass, and Kalman filter.

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