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REVIEW ARTICLE

Robust Control Techniques for Electrical Machines in Wind and Solar Energy Applications

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***Abstract*—An investigation analyzes performance-enhancing methods for renewable energy system electrical equipment, especially solar and wind power generators, through strict management systems. Solar and wind power technologies increase in importance which leads to the necessity of complex control systems to address unpredictable characteristics in these power systems. Robust control strategies, including H∞ control, Sliding Mode Control (SMC), and Model Predictive Control (MPC), offer effective solutions for managing variability of environmental conditions, like fluctuating wind speeds and solar irradiance. The mentioned techniques enable the achievement of maximum energy conversion performance together with fault detection systems and reliable system operation. The essay explores both adaptive control systems that adapt through methods like fuzzy logic with neural network systems to enhance dynamic operating performance in their application to power systems. The paper concludes by highlighting future research directions, including the integration of machine learning with robust control techniques to enhance real-time adaptability and scalability in large-scale renewable energy systems.**

Keywords*—Robust control, renewable energy, wind power, solar energy, H∞ control, Sliding Mode Control, Model Predictive Control, adaptive control, intelligent control, energy efficiency, fault detection, system reliability.

I. INTRODUCTION

The field of "robust" linear control systems theory has experienced significant advancement since the beginning of the last decade. The tool exists as a vital resource that continues to grow popular for use in industrial servo system analysis and design. Applied character together with real-world relevance to automation engineer issues serve as major factors behind rapid acceptance of this method. Let's review the two fundamental roles of control in order to understand the novelty and appeal of robust control tools: directing the servo system's reaction to produce the desired behavior and preserving that behavior against operational variations [1].

The world's energy generating priorities have been changing towards renewable sources including wind, solar, biofuels, and tidal streams as a result of concerns about fossil fuel pollution and energy security. Wind power production stands out among these renewable energy sources due to its rapid growth and increased interest from both academics and businesses [2]. The field of "wind power generation" is quite popular right now as, when combined with other renewable energy sources, it provides a clear and sustainable way to generate electricity [3]. Variable-speed electric machine-drive systems are gradually replacing fixed-speed ones, which were common until twenty years ago.

This occurs as a result of its build-in drawbacks, which include inefficient wind energy conversion, rigidity in assisting with grid voltage adjustment, unavoidable power flicker, and mechanical stress problems caused by wind gusts [4]. It was shown that these Vernier PM machines with outer rotors may operate at low speeds to directly harvest wind energy and allow for high-speed rotating field designs to optimize power density [2].

There are numerous uses for solar energy in their daily lives, including cooking, hot water supply, and home heating. Intermittence is one of the main disadvantages of solar energy [5]. Most places that use solar energy will need some sort of energy storage technology to help with this problem. Energy storage systems come in several forms. Electrical power generation is a crucial area where solar energy is being applied. Here, the sort of technology used to generate electricity determines which energy storage system is optimal. Photovoltaic (PV) and Concentrated Solar Power (CSP) are two options for using solar energy to generate electricity [6].

A. Structure of the paper

This paper is organized in the following way: Section II overview of electrical machines in wind and solar energy systems. Section III discusses Robust control techniques for electrical machines. Section IV addresses robust control for wind and solar energy applications. Section V reviews literature and case studies. The results and directions for further study are presented in Section VI.

II. OVERVIEW OF ELECTRICAL MACHINES IN WIND AND SOLAR ENERGY SYSTEMS

Machines that transform mechanical energy, which is frequently produced by renewable sources, into electrical energy are essential components of renewable energy systems [7]. These machines are integral to the operation of devices such as wind turbines, solar power systems, and hydroelectric plants, enabling efficient energy production and distribution. Here's a breakdown of their role:

A. Wind energy system

Systems that harness wind power transform the mechanical energy of the wind into usable electrical energy. These systems are a key component of renewable energy solutions and are used worldwide to generate electricity in a sustainable way shown in Figure 1. Wind energy systems primarily consist of wind turbines (which capture the wind's energy) and various electrical components (which convert and store that energy). The main parts of a standard wind power system are listed below [8]:

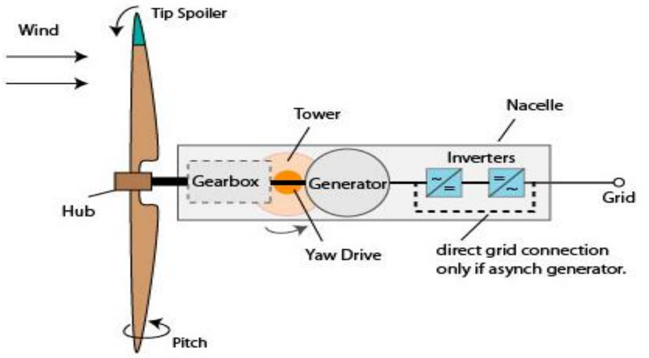

Fig. 1. The wind energy system

- **Wind Turbine:** The central machine that captures wind energy and converts it into mechanical energy [9].
- **Rotor Blades:** The purpose of the blades is to harness the energy of the wind. A wind turbine harnesses the kinetic energy of the wind by spinning its blades in response to the wind's velocity [10].
- **Hub:** The attachment point for the rotor blades is the hub. It connects the blades to the rest of the turbine system.
- **Nacelle:** At the very top of the tower sits the nacelle, which contains the control systems, generator, and gearbox of the turbine.
- **Gearbox:** The gearbox is responsible for adjusting the turbine blades' rotating speed so that it produces the maximum amount of power.
- **Generator:** Electricity is produced when the mechanical energy of the spinning blades is transformed into it by means of the generator [11].
- **Tower:** A tower holds a turbine at a height to capture stronger, more consistent winds. The height also minimizes turbulence and maximizes efficiency.
- **Yaw Mechanism:** This mechanism rotates the nacelle and rotor to face the wind direction. It ensures the turbine is aligned with the wind for maximum energy capture [12].

B. *Solar energy system*

The term "solar energy system" refers to a collection of interconnected components, such as photovoltaic (PV) panels, a storage container, and any number of collectors that work together to convert sunlight into usable heat or cold for a building's interior or water heating needs [13]. The two most common forms of solar power systems are photovoltaic (PV) and solar thermal [14]. Here's an overview of how each type works displayed in Figure 2:

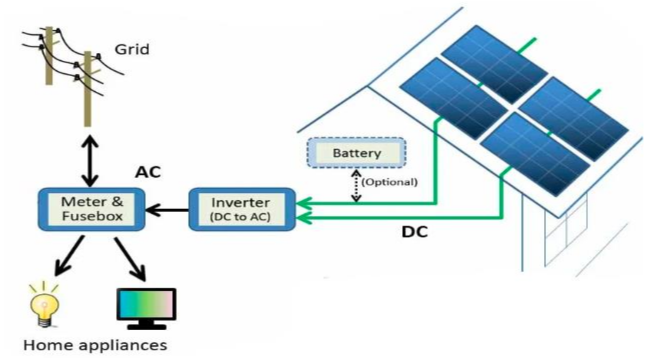

Fig. 2. The solar energy system

1) Photovoltaic (PV) Solar Energy Systems:

The use of semiconductor materials in solar panels allows photovoltaic systems to directly convert sunlight into electricity (such as silicon). Sunlight hitting these panels' surfaces triggers an electrical current [15]. There are Components of a Photovoltaic System:

- **Solar Panels:** Arrays of solar cells that work together to form a PV system's core. By utilizing the photovoltaic effect, these cells transform sunlight into DC electricity [16].
- **Solar Cells:** These are made of semiconductors (usually silicon) that absorb photons (light particles) from sunlight, causing electrons to be knocked loose and creating an electrical current [17].
- **Inverter:** Although DC electricity is produced by solar panels, the majority of electrical equipment, including homes and networks, utilize AC electricity. Solar panels produce DC, but an inverter changes it to AC [18].
- **Mounting System:** A structure that holds a solar panel in place. It can be roof-mounted or ground-mounted, depending on the installation type.
- **Charge Controller (in off-grid systems):** Overcharging can occur in systems that are not linked to the grid because a charge controller controls the amount of energy that goes into the batteries from the solar panels.
- **Batteries (in off-grid systems):** During periods when the sun isn't shining, like at night or on overcast days, these stores extra electricity produced by the panels.
- **Grid Connection:** In grid-tied systems, surplus power can be returned to the grid, potentially earning credits for the business or homeowner.

2) Solar Thermal Energy Systems:

Sunlight is captured by solar thermal energy systems to produce heat, which can be utilized for a number of purposes, including heating water or spaces or, in larger systems, producing electricity [19]. These systems differ from photovoltaic (PV) systems in that they don't generate electricity directly from sunlight but rather use solar energy to heat a medium, which can then be used for heating or power generation. There are some components of solar thermal energy system:

- **Heat Transfer Fluid:** This fluid (often water or antifreeze) absorbs the heat collected by the solar collector and carries it to other parts of the system, such as a storage tank or a heat exchanger.
- **Storage Tank:** The heat transfer fluid is stored in a tank where the heat can be retained for later use, especially during times when the sun is not shining, such as at night.
- **Heat Exchanger:** In some systems, the heat transfer fluid is passed through a heat exchanger, which then heats the water or air in the building for domestic use or space heating [20].
- **Pumps and Valves:** These components circulate the heat transfer fluid through the system in active solar thermal systems, helping to move the fluid from the collectors to the storage tank or heat exchanger.
- **Controller:** This is used to monitor and control the operation of the system, ensuring that the fluid flows

through the system at the right temperature and that the system operates efficiently [21].

III. Robust Control Techniques For Electrical Machines

Robust control techniques are designed to maintain system stability and performance despite uncertainties, disturbances, and variations in system parameters. In the context of electrical machines, particularly in renewable energy applications (such as wind and solar), these techniques are crucial due to the inherent unpredictability of environmental conditions (fluctuating wind speeds or solar irradiance) and the nonlinear behavior of the systems involved [22].

A. Classical control approaches

Classical control approaches like Proportional Integral Derivative (PID) control and Linear Quadratic Regulator (LQR) are commonly used for controlling electrical machines:

- PID control is a straightforward and efficient method that modifies the control input according to the error, accumulated error, and rate of change of error by combining three components: proportional, integral, and derivative.
- While easy to implement, PID control struggles with systems having significant uncertainties or parameter variations and is typically used in speed or torque control for synchronous and induction motors [23].
- LQR, on the other hand, is an optimal control strategy that minimizes a cost function to balance control effort and deviation from the desired state.
- However, its assumption of linear system dynamics makes it less effective for nonlinear systems, such as electrical machines in wind and solar energy applications.
- LQR is often used in managing system behavior to ensure optimal performance under normal conditions.

B. Modern robust control methods

Modern robust control methods, such as H∞ control, SMC, and MPC, offer enhanced performance in systems with uncertainties and disturbances:

- H∞ control minimizes the worst-case gain of a system, ensuring robustness against model uncertainties and external disturbances, making it highly effective for electrical machines operating under variable conditions, such as wind turbines and solar inverters.
- Sliding Mode Control, a nonlinear technique, drives the system to a predefined sliding surface, ensuring robust performance despite parameter variations or disturbances, and is particularly useful for controlling variable-speed wind turbines [24].
- Model Predictive Control optimizes control inputs by predicting future system states, solving an optimization problem at each time step while considering constraints, and is widely used in renewable energy systems like solar or wind inverters to control voltage and current.
- These methods provide superior performance compared to classical approaches, especially in the presence of complex, time-varying conditions.

C. Adaptive and Intelligent Control Methods

Adaptive and intelligent control methods, like Adaptive Control, Fuzzy Logic, and Neural Network-based control, are effective in managing systems with uncertain or dynamic conditions [25]. Systems with time-varying characteristics, like renewable energy applications, benefit greatly from adaptive control since it modifies control settings in real time depending on observed system performance [26].

- The control method finds its main application in electrical systems with variable-speed drives, like wind turbine generators operating under frequent fluctuations.
- Control decisions made by knowledge-based systems are enabled through fuzzy logic as well as through neural networks.
- Fuzzy logic controllers deal with uncertain situations combined with approximate reasoning through methods that align well with nonlinear systems that cannot be properly modeled mathematically.
- Power conversion efficiency of solar energy systems and fault detection and energy capture optimization in wind turbine control systems rely on these techniques within electrical machines.

IV. Robust Control For Wind And Solar Energy Applications

This research field focuses on developing dependable operations for renewable energy systems such as wind turbines together with solar power converters under environment-based uncertainties and changes. The operation of these systems depends on stable wind speed and solar insolation as well as various environmental components, which might result in performance decline or devastating system instabilities [27].

A. Robust control for wind energy application

The stability operational efficiency and reliability of wind-based power systems represents the core objective of Robust Control for Wind Power Systems [28]. Robust control techniques are applied to handle these uncertainties and ensure consistent performance. Here are the key points explaining robust control for wind power systems:

1) Handling Variable Wind Speeds:

The wind turbines are highly sensitive to the change in wind speed. The turbine system uses H∞ control and Sliding Mode Control (SMC) robust control methods to deal with wind speed fluctuations while maintaining its best operational state [29].

2) Stability under Uncertainty:

The system stability against unknown system parameter changes is guaranteed by robust control methods [30]. The system acts according to a pre-defined sliding surface that lets it follow this path of operation while the turbine operates at an optimal load.

3) Fault Detection and Fault Tolerance:

The robust control system detects faults in real-time through events like mechanical breakdowns or electrical problems which lead it to modify control inputs. Such operational control ability strengthens wind power systems against faults to preserve automatic operations while reducing system stoppages.

4) Optimizing Power Output:

Wind power system can optimize the power output by optimizing between changing wind conditions using MPC or Adaptive Control techniques.

5) System Integration and Grid Stability:

Great control systems help electrical grids accept wind power systems in an efficient manner. The power generation system of wind turbines requires constant electricity output quality under unstable wind conditions [31].

6) Load Shedding and Protection:

Strong control systems provide a method to activate load shedding together with protection procedures that safeguard wind turbine systems from harm while maintaining operational safety.

B. Robust control for solar energy application

The focus of Robust Control for Solar Energy Applications centers on uninterrupted stable power conversion operations in solar systems, particularly solar inverters, while solar irradiance and environmental factors change. Changes in sunlight, as well as temperature and external environmental elements, affect how solar energy systems function [32]. Here are the key points that explain robust control for solar energy applications:

1) Handling System Uncertainties:

Changes in temperature along with component deterioration throughout time result in uncertainties regarding solar energy system parameters. The system performances under changing environmental conditions can be optimized through Adaptive Control and SMC which handle the uncertainties.

2) Fault Detection and Protection:

Robust control methods act as a detection system for faults that occur within the system by identifying component failures and solar inverter malfunctions. Through automatic adjustments, the system blocks additional harm to components while sustaining its power generation, thus extending the operational lifespan of the solar power system.

3) Grid Integration and Power Quality:

For solar energy grid integration, synchronization with the grid and power quality are crucial issues. Robust control provides sustained characteristics for the frequency regulation along with voltage stability of the grid [33].

4) Dynamic Load Handling:

The solar power system faces changing loads and energy demands by the devices connected. The precise power output of the solar inverter can be dynamically adjusted based on various robust control methods to match the requirements of the load, thereby achieving efficient operation of the system even when the demand changes [34].

5) Maximize energy harvesting:

Solar irradiance, available for a particular application of solar energy, must be fully harnessed for maximum energy extraction. Adaptive control techniques will be capable of adjusting the operational parameters of the solar inverters in real time.

V. Literature Review

This section presents earlier studies on robust control methods for electrical machines used in solar and wind energy applications.

In, Zhao et al. (2006) examine the yaw control of a small-scale helicopter installed on an experimental platform using a novel, reliable controller design technique. A linear system that is modeled by an affine uncertainty model is created by linearizing the yaw dynamic system. With guaranteed control performances, they suggested a new robust feedback controller for the linear system that has adaptive mechanisms. The solutions of a sequence of LMIs yield feedback gains. The design method enhances time-response performance while reducing conservatism that comes with robust control using a fixed gain controller[35].

In, Dimri, Kaur and Deepika (2023) examines different robust control methods for controlling the frequency of loads in an islanded microgrid that consists of energy storage systems (ESS), such as FES and BES, and distributed generators, including DEGS, microturbine (MTs), and fuel cell (FCs). A thorough analysis of the microgrid's performance is carried out in the presence of changeable load perturbation and variable wind power. In order to find the optimal controller, the results are compared[36].

In, Biasion et al. (2021) offers an overview of the latest uses of superconductors in electrical machines that spin. In order to emphasize their primary characteristics, the most common kinds of superconductors used in modern electrical applications are displayed. The data of prototypes and demonstrators are used to highlight the major features of superconducting synchronous machines, DC machines, and induction machines for industrial applications, future electric aviation, marine and vehicle propulsion, wind energy, and more[37].

In, Rama Mohan (2021) showcases a liquid sprayer that runs on solar power and has uses in agriculture, the environment, and healthcare. One possible agricultural use for the suggested liquid sprayer is the application of insecticides. Environmental uses for the hypo liquid include spraying down street drains to eliminate insects and microorganisms. In order to fuel the spraying process, the proposed sprayer makes use of solar electricity. The suggested sprayer just requires one operator[38].

In, Choi and Jahns (2013) showcases an electric machine design assessment tool tailored for EVs, with the goal of optimizing the machine's performance in the operational zones that align most closely with the EV’s driving schedules. Research is conducted on the effects of various designs on a mass-produced battery-electric car. The expected machine and vehicle performance parameters are used to determine the total necessary energy and relative losses for each of the candidate machines throughout the driving cycles[39].

In, Kewat and Singh (2021) discusses a reliable method of controlling a DGS that may function in either an isolated or grid-connected configuration. A robust inner-loop quadrature second-order generalized integrator-based phase-locked loop and a bidirectional DC-DC converter control approach are given to mitigate this issue. The MATLAB/Simulink platform validates the efficacy of this DGS control technique in the presence of load imbalance, variations in solar irradiation, and switching modes. Furthermore, the modeling findings are confirmed by the test results, demonstrating that the control method remains resilient even in the face of aberrant grid voltage conditions[40].

In, Nasiri, Mobayen and Arzani (2022) using this control method, the BTB-converter controllers become more resilient to parameter uncertainty and external disturbances, and their reaction time is reduced. When faults occur, the active power output of the generator quickly decreases because the gridside converter follows the maximum power point. The simulation talks concentrate on comparing the implemented PID-TSMC approach to alternative BTB-converter control systems in terms of their resilience and efficiency[41].

This Table I provides a structured comparison of each reference, focusing on its key contributions, performance benefits, and areas for future enhancement.

TABLE I. LITERATURE ON ROBUST CONTROL FOR ELECTRICAL MACHINES IN WIND AND SOLAR ENERGY

References	Focus on	Performance	Limitations & Future Work
[35]	Robust controller design for yaw control of a small-scale helicopter	Reduced conservatism in robust control, improved time-response performance	Requires experimental validation on real-world helicopters
[36]	Robust control techniques for load frequency control in an islanded microgrid	Improved stability under variable load perturbation and fluctuating wind power	Optimization of control parameters for different renewable energy sources
[37]	Applications of superconductors in rotating electrical machines	Highlighted key features of superconducting machines for marine, aerospace, and industrial applications	Further research needed on cost reduction and large-scale implementation
[38]	Solar-powered liquid sprayer for agricultural and environmental applications	Effective in spraying pesticides and disinfectants using solar energy	Needs testing for large-scale agricultural deployment and efficiency improvements
[39]	Design evaluation tool for electric machines in electric vehicles	Maximized machine efficiency for specific driving schedules	Further exploration of machine optimization for real-world driving conditions
[40]	Robust control strategy for a distributed generation system (DGS)	Improved robustness under load variations and abnormal grid voltage conditions	Needs real-world implementation and hardware validation
[41]	Robust control scheme for BTB-converter controllers	Decreased response time and enhanced robustness against parameter uncertainties	Comparison with more advanced control techniques for further improvements

VI. CONCLUSION AND FUTURE SCOPE

The integration of robust control techniques in renewable energy systems, particularly wind and solar energy applications, plays a vital role in enhancing system performance and stability amidst unpredictable environmental conditions and operational uncertainties. Basic control operations provided by PID and LQR controllers are insufficient for handling non-linear behavior together with parameter fluctuations that exist within renewable energy systems. Modern robust control techniques including H∞ control SMC and MPC improve the system performance by guaranteeing stability and optimal power output and fault tolerance for dynamic systems under uncertain conditions. The performance of systems highly benefits from adaptive and intelligent control methods incorporating fuzzy logic and neural networks since they learn and adjust in real time. Strong control methods enable turbines and solar inverters to execute flawlessly in wind and solar energy systems, thus enhancing their ability to connect with the grid as well as their capability to detect faults manage loads and extract maximum energy output. These procedures protect energy transformation effectiveness and power grid stability by resolving the frequent interruptions in renewable power generation.

Researchers in robust control theory should explore better interfaces between artificial intelligence and traditional robust control in renewable energy systems with priority areas in wind and solar generation. The combination would lead to enhanced real-time systems performance under unpredictable weather conditions as well as fast-changing environmental solar irradiance and wind speed levels. Furthermore, developing hybrid control strategies that combine the strengths of model-based, adaptive, and data-driven methods could lead to more resilient and efficient systems, capable of optimizing energy capture and grid stability while minimizing downtime and maintenance costs.

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