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Robust Control of Electrical Machines in Renewable Energy Systems: Challenges and Solutions

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Abstract:- The increasing global demand for energy driven by population growth necessitates a shift towards renewable energy sources to address sustainability and environmental concerns. Renewable energy sources and how they function in tandem with electrical equipment to generate power are covered extensively in this study. Renewable sources like solar-thermal, hydro, wind, wave, tidal, geothermal, and biomass-thermal utilize electric machines to convert various forms of stored energy into electricity. The paper classifies these machines based on their design and application in renewable systems, highlighting the most common types, including DC, induction, and synchronous machines. It also evaluates their performance according to efficiency, power density, and cost-effectiveness. A primary focus is on the challenges associated with controlling electrical machines in renewable energy systems, including issues related to intermittency, grid integration, nonlinear dynamics, fault tolerance, harmonics, efficiency optimization, thermal management, scalability, real-time control, and cost constraints. The paper concludes by discussing the need for advanced control strategies and solutions to address these challenges, aiming to enhance a reliability, efficiency, and performance of renewable energy systems.

Keywords:- *Electrical Machines, Renewable Energy, Challenges, Solutions, Classification.*

I. INTRODUCTION

Electric devices with high specific torque are highly sought after for low-speed renewable energy applications, including tidal and wind turbines. This fascination has been recently heightened by the necessity of high torque machinery for direct drive wind or tidal turbines [1]. Electrical machines play a vital role in renewable energy systems, converting energy from sources like wind, solar, and hydropower into electrical power. In order to convert the mechanical energy generated by wind turbines into electrical energy, wind energy systems frequently employ generators such as synchronous and induction machines. These machines are essential for ensuring efficient energy conversion, where modern designs focus on improving performance, reliability, and efficiency to meet a growing demandfor renewable energy[2].

In solar energy systems, electrical machines are involved in processes such as tracking and positioning solar panels to optimize energy capture[3]. Motors and actuators ensure that solar panels are oriented to receive maximum sunlight throughout the day, thus improving the efficiency of photovoltaic (PV) systems[4]. In addition, grid-connected inverters, which function as essential components in solar power plants, require reliable electrical machines to maintain a stable power output by converting DC to AC power. Hydropower systems also rely heavily on electrical machines, particularly synchronous generators[5], to convert a kinetic energy by water turbines into electricity. These machines are crucial in large-scale hydroelectric plants, providing efficient and steady power generation. An integration of electrical machines in renewable energy systems requires innovation to meet the challenges of energy storage, grid compatibility, and variable energy inputs, making them an indispensable part of the shift toward sustainable energy solutions. This paper contributes to the field of robust control of electrical machines in renewable energy systems by:

- Identifying Key Challenges: It outlines critical issues such as intermittency, grid integration, and nonlinear dynamics affecting control.
- Evaluating Control Strategies: It reviews and compares various robust control methods, including model predictive and adaptive control, for managing renewable energy systems.
- Providing Practical Insights: Through case studies and simulations, it demonstrates real-world applications and effectiveness of control strategies.
- Suggesting Future Research: It highlights areas needing further investigation to enhance control system robustness and adaptability.
- Overall, the paper advances both theoretical understanding and practical approaches to enhancing a reliability and efficiency of renewable energy systems.

➢ *Structure of this Paper*

The structure of the paper is as follows: Section I: Introduction discusses the need for renewable energy and electrical machines' roles. Section II: Renewable Energy Sources covers types like wind and solar. Section III: Classification of Electric Machines details DC, induction, and synchronous machines. Section IV: Existing Machines for Renewable Energy evaluates performance and cost. Section V: Challenges and Solutions addresses control issues and suggests improvements. Section VI: Literature Review summarizes relevant research. Section VII: Conclusion and Future Work highlights findings and future research directions.

II. RENEWABLE ENERGY SOURCES

The world's population is expanding, which is causing a significant increase in energy consumption. Energy production becomes a global concern. One popular strategy for addressing energy production is an utilisation of renewable energy sources. Energy that originates from naturally occurring resources that are not exhausted through use is known as renewable energy. Biomass, often known as biofuel, wind, solar, and water power are the four most common forms of renewable energy. These energy sources have long been used for things like heating, electricity production, and fuelling vehicles. The sustainability of renewable energy sources makes them interesting. This results in a replacement for the exhaustion of conventional energy sources like coal, petroleum, and nuclear power with a new kind of renewable-energy. An environmental impact of renewable energy sources is far lower than that of conventional power plants and other conventional energy infrastructure [6]. Energy access is crucial to a nation's ability to prosper economically. Power consumption in developing countries typically rises 1.4% for every 1% growth in GDP [7][8].

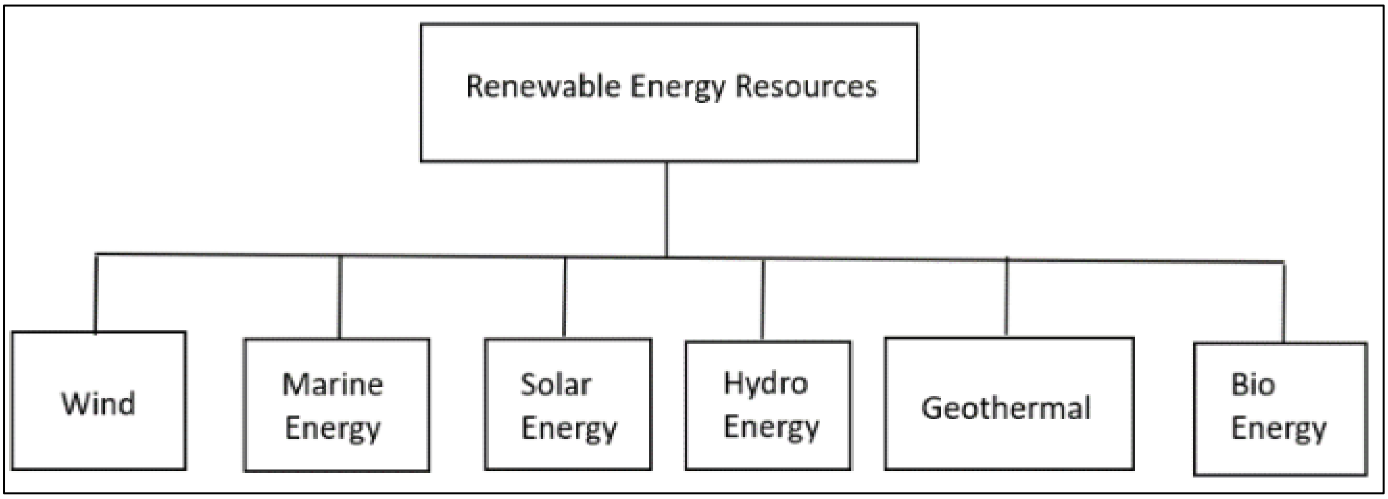

Fig 1 Overview of Renewable Energy Resources[9].

Resources for renewable energy are summarised in Figure 1. The globally accessible renewable energy sources are these (Figure 1). Due to its enormous emissions of greenhouse gases, petroleum-based energy now accounts for 60% of global carbon emissions and plays a significant impact in climate change. GHGs, which encircle the world like a blanket and trap heat in the atmosphere, include CO2, N2O, and CH4 [10][11]. The blanket becomes very thick and dense, making it less probable for heat to leave the planet as more coal, natural gas, and oil are used by people. Many negative effects on the ecosystem result from heat being trapped under the GHG blanket and making the Earth too heated. Because of this crucial aspect, a number of researchers have been concentrating on finding the best way to incorporate renewable energy sources into power generation. The energy sources that are continually renewed by nature are known as renewable energies [12]. Renewable energy also includes energy produced by other environmental natural processes like tidal and geothermal energy. Energy supplies obtained from ecologically hazardous fossil fuels and waste materials from inorganic or fossil sources are not included in the definition of renewable energy. It is thus endlessly renewable, ensuring that there will always be an energy source that is free of pollutants and does not contribute to greenhouse gas emissions or global warming.

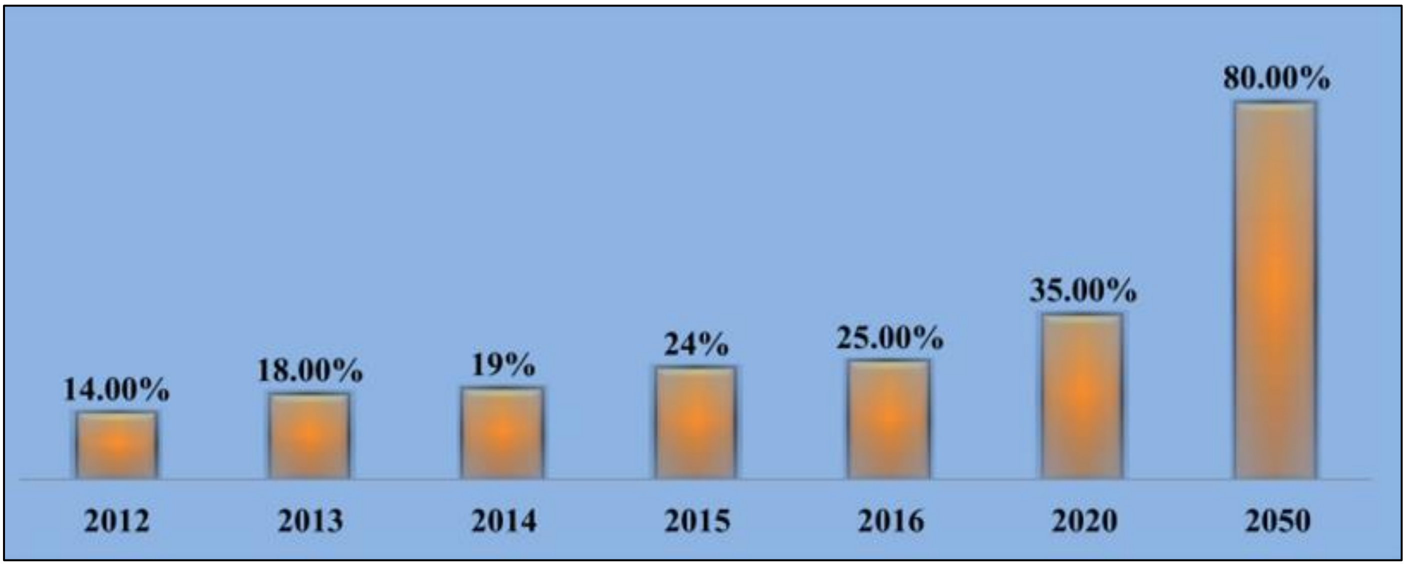

Fig 2 Increasing Rate of Energy Generation from Renewable Energy Sources in Present and Future [13]

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Figure 2 displays the percentage of renewable energy, which includes the historical, current, and projected rates of energy generation by renewable sources. A most promising kind of renewable energy is wind power.

III. OVERVIEW OF RENEWABLE ENERGY IN ELECTRIC MACHINES

There is a presentation of renewable energy sources that use electric machines to generate electricity, including geothermal, wind, solar-thermal, wave, tidal, hydro, and biomass-thermal; however, solar-electric(photovoltaic) and thermoelectric power generation, which directly generate electricity without utilizing electric machines, will not be covered [14][15]. Renewable energy sources can be broadly classified according to the forms of energy storage they employ prior to electric machine generation. For example, kinetic energy is stored by wind, waves, run-of-river hydro, and tidal streams; potential energy is stored by large hydro and tidal barrage; and heat energy is stored by solar thermal, geothermal, and biomass-thermal sources[16].

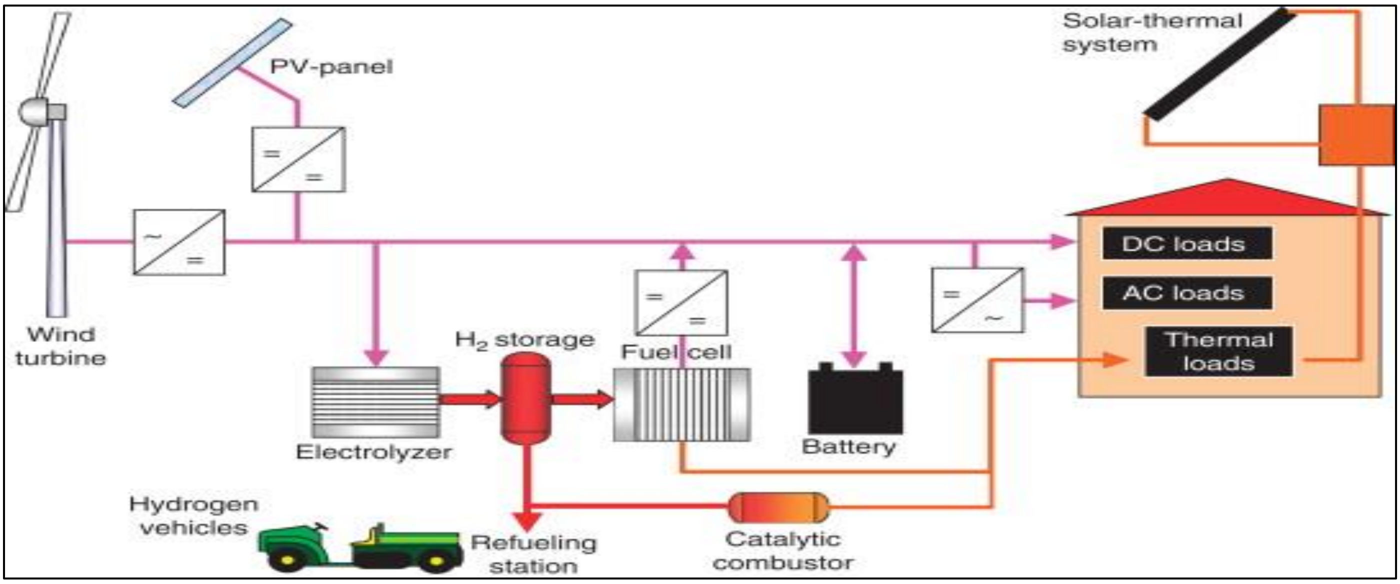

Fig 3 Renewable Energy Source

The capacity factor compares the peak power to the average power over a given time period and finds that wind turbines account for 30% of solar energy while solar panels account for 20%. An RFC may convert power to hydrogen when renewable sources are abundant, storing the extra energy. When renewable sources are unavailable, the hydrogen can be utilised to create electricity, as seen in Figure 3. An interface among a renewable energy source and a RFC system has to be compatible with the current and voltage of both, since solar and wind systems have different specifications. Direct current from photovoltaic solar systems may be utilised directly by the electrolyser if their polarisation curves match; if not, a DC/DC converter could be required. An AC/DC inverter, similar to the controlled voltage power supply of the electrolyser, is a need for the interface as wind turbines normally produce AC.

These energy storage methods serve as the foundation for the majority of electric machine types [17][18].

- *Wind Power:*

Energy from moving air, or wind, is what is fundamentally known as mechanical energy. The mechanical energy generated by a wind turbine is often transformed into electricity by electric equipment. Usually, wind turbines may be anything from 1.5 MW to 7.6 MW in capacity. An assembly of wind turbines is known as a windfarm. The Indian Jaisalmer Wind Park, with a capacity of 1064 MW, is the biggest wind farm in the world right now.

- *Wave Power*

Kinetic energy of waves travelling over the ocean's surface is known as ocean power or marine power [19]. A construction of wave power facilities is moving at a snail's pace, despite the fact that the worldwide potential for wave power production is predicted to reach 12,500 TWh per year.

- *Hydropower*

Utilizing the natural flow of fresh water towards the ocean to produce energy is known as hydropower generating, and it is the most established kind of renewable energy harvesting. Most notably, reservoirs created by dams allow for the conversion of the potential energy differential between water levels upstream and downstream into electrical energy, making this method both visible and effective.

- *Tidal Power:*

An increasingly developed method of producing energy from the movement of seawater between high and low tides is called tidal power production. A tidal barrage is a common way to harness the power of the tides. The process converts potential energy into electrical energy by releasing water from dams at low tide, which occurs about every twelve hours, after it has been stored during high tide. A tidal stream is another possibility; it harnesses the energy of the water's motion to produce electricity during the six-hour high and low tide cycles.

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➢ *Solar-Thermal Power*

A term "solar power" describes the way in which the sun provides energy to our planet. There are two main techniques to convert solar energy into DC. One is solar thermal power, which uses solar parabolic troughs and power towers to concentrate the sun's rays, boil water, and then generate electricity via a steam turbine and generator. Photovoltaics uses semiconductors with a photovoltaic effect.

➢ *Geothermal Power*

The process of extracting thermal energy from the Earth's surface and transferring it to steam turbines, which run generators, is known as geothermal energy generation. The three main ways that geothermal energy can be harnessed to produce power are: the dry steam plant, which uses steam with a minimum temperature of 150◦C to directly power turbines; the flash steam plant, which uses steam with a minimum temperature of 182◦C to drive turbines; and the binary cycle plant, which uses heat exchangers to transform secondary fluids from geothermal hot water with a minimum temperature of 57◦C into vapour.

➢ *Biomass-Thermal Power*

The process of creating energy from organic materials is known as "biomass power generation." It might include burning biomass fuels like bagasse, residues, and wastes directly or converting them into other forms of energy like liquid biofuel and useable biogas [20][21]. Nowadays, the majority of biomass power is produced by biomass-thermal plants, which use the combustion of wood and agricultural waste to produce steam, which is then used to generate electricity.

➢ *Comparison*

Table 1 compares the different kinds of electric machinery and the related power conditioning needs [22] based on the previously described renewable power production technologies. All of the aforementioned power plants—wind, wave, geothermal, biomass, small hydro, run-of-river, tidal stream, and big hydro—use the same equipment and power converters to convert linear wave motion into rotating motion. It goes without saying that the electric equipment used to generate direct-drive wave power is special.

Table 1 Existing Machines for Renewable Energy.

Renewable energy	Machine	Power conditioning
Wind	SG, IG, DFIG, PMSG	Optional, AC-DC-AC
Wave (rotational)	SG, IG, DFIG, PMSG	Optional, AC-DC-AC
Wave (linear)	LPMSG	AC-DC-AC
Large hydro	SG	NA
Small hydro	IG, PMSG	AC-DC-AC
Tidal barrage	SG	NA
Tidal stream	IG, PMSG	AC-DC-AC
Solar-thermal	SG, IG	NA
Geothermal	SG, IG	NA
Biomass-thermal	SG, IG	NA

IV. CLASSIFICATION OF ELECTRIC MACHINES

Various types of electric devices are derived from the numerous different topologies. They were formerly divided into DC and AC categories. This category is going to be inadequate as new kinds of machines appear. The suggested categorisation of electric machines is shown in Figure 4, with the kinds in bold used for the production of renewable energy while the branches deemed unsui Table for this purpose have been trimmed[23]. Commutator and commutator less are the two main ways to classify them. You can tell the difference between the two just by looking at the fact that one has carbon brushes and the other has a commutator. It should be mentioned that the tendency is concentrated on creating novel kinds of commutator less machines.

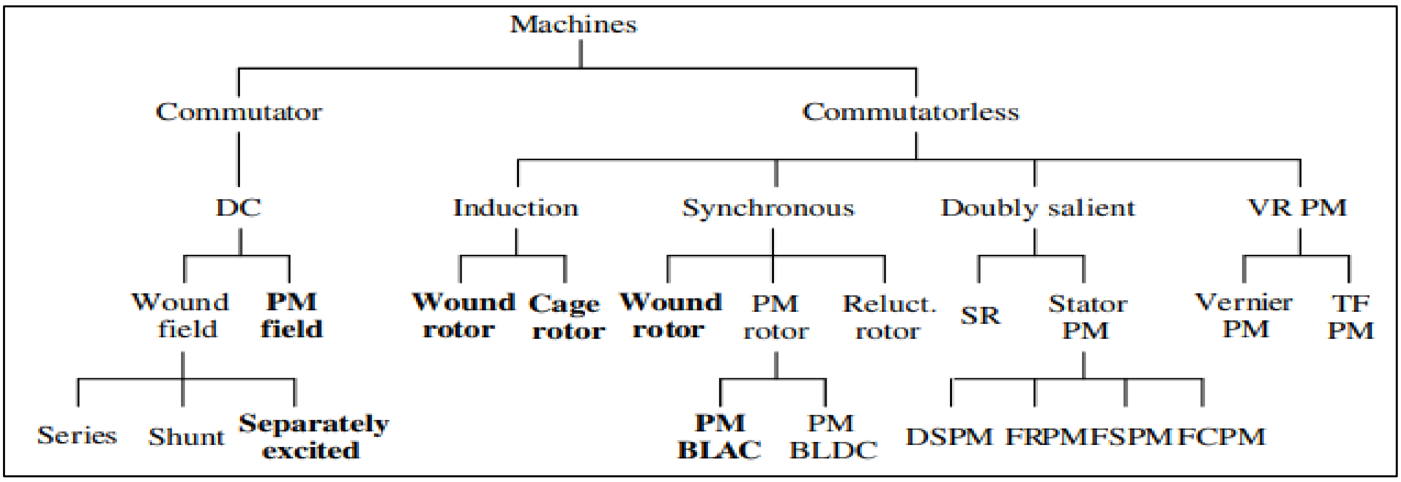

Fig 4 Classification of Electric Machines.

Electric devices intended for industrial use should not be seen as a subset of those intended for renewable energy collecting due to their fundamentally different needs. The machine that uses renewable energy should belong to a distinct class of electric machines that has the following characteristics:

- Excellent efficiency throughout a broad range of torque and speed, leading to greater use of usable energy;
- The ability to minimise size and weight thanks to a high power density;
- The ability to capture energy at a variety of speeds;
- Extreme dependability to cut down on operational failures and faults;
- Maintenance-free to save maintenance expenses and potential downtime for maintenance;
- Extreme durability to endure the elements and demanding work circumstances;
- Reliable voltage regulation to keep the system voltage constant;
- A high power factor to provide more efficient power transmission;
- Affordable to a minimum in order to lower system costs.

V. EXISTING MACHINES FOR RENEWABLE ENERGY

Electric machines come in many forms, but three of the most common have found use in renewable power generation: synchronous, induction, and DC.

➢ *DC Machines*

The field excitation methods used to classify DC machines distinguish between two types: self-excited DC machines and separately excited DC machines. Additionally, wound-field DC and PM DC types may be applied based on the field excitation source. The full family consists of four types of DC motors: individually excited, shunt, series, and PM DC. Differentiating features of these kinds include the presence of PM excitation or connections between the field and armature windings. The DC machine that is independently stimulated has separate armature and field circuits. There is a parallel connection between the shunt DC machine's field and armature circuits. Circuitry connecting a field and armature is a typical component of series DC machines. When it comes to the PM field, the PM DC machine has no control. Compared to wound-field machines, PM DCs are more efficient and have a higher power density due to the space-saving properties of PMs and the lack of field losses [24].

➢ *Induction Machines*

Among the many types of commutatorless machines, induction machines have reached a state of technological maturity [25]. You may find induction devices with wrapped rotors or cage rotors. When it comes to wound-rotor induction machines, another name for them is slip-ring induction machines. This is because the rotor winding is connected to the outside circuit using carbon brushes and slip rings. One common method for harnessing wind energy is the wound-rotor induction generator, or DFIG. When linked to the grid, the stator winding allows a frequency converter to regulate the slip power. Wind power DFIGs are manufactured by a number of major companies, including Acciona, Gamesa, General Electric, Alstom-Ecot'ecnia, Repower, Mitsubishi, and Vestas. For example, the Alta Wind Energy Centre has 390 Vestas DFIGs, which provide a combined 1.5 MW or 3 MW of installed capacity, making it the largest wind farm in the US. It can handle loads up to 1020 MW. The ability of DFIGs to maintain output frequency synchronisation with the grid in the face of varying wind speeds is the fundamental factor driving their adoption in wind farms. Nevertheless, a wound-rotor induction-machine or a derivative DFIG is losing appeal to newer generation wind farms due to its lack of durability and maintenance requirements. The DFIG is not desirable for other forms of renewable energy harvesting, with the exception of wave power collecting employing wind turbine technology.

➢ *Synchronous Machines*

Fossil fuel power production nearly entirely uses synchronous machinery. Thermal power plants and hydropower facilities both rely heavily on them due to the consistent speeds maintained by the steam turbines and hydro turbines, respectively, used in these facilities. In general, synchronous machines may be grouped into two types: and Wound-rotor [26]. Typically, a wound-rotor synchronous machine will use carbon brushes and slip rings to attract DC current from an external source, and the DC field winding will be incorporated within the rotor itself. This woundrotor synchronous machine, often known as the SG for short, is typically appealing to high power rating renewable energy generating systems.

➢ *Comparison of Existing Machines*

Several factors are taken into consideration when assessing the suitability of these machines for use in renewable energy collection applications. These include power density, efficiency, power factor, maturity, power conditioning required, robustness, power level, cost, maintenance requirements, and cost. The method of grading is based on a point system, where 1 represents the poorest and 5 represents the greatest. Table 2 clearly demonstrates that the wound-field and PM DC devices are not very attractive. Machines using wound rotors, cage rotors, and wound synchronous motors are all workable alternatives to the ideal wound rotor machine. Conversely, the PM synchronous machine is perfect.

Table 2 Evaluation of Existing Machines for Renewable Energy

	Wound DC	PM DC	Wound Ind	Cage Ind	Wound Syn	PM Syn
Efficiency	2	3	3	4	4	5
Power density	2	3	3	4	3	5
Powerfactor	5	5	4	3	5	5
Power conditioning	3	3	5	3	3	3
Robustness	2	2	4	5	4	4
Maturity	5	5	5	5	5	4
Cost	3	3	3	4	4	3
Power level	2	2	4	4	5	4
Maintenance	2	2	3	5	4	5
Total	26	28	34	37	37	38

VI. CHALLENGES AND SOLUTION OF CONTROLLING ELECTRICAL MACHNIES IN RENEWABLE ENERGY SYSTEMS

Controlling electrical machines in renewable energy systems presents several challenges due to the unique characteristics of renewable energy sources and the operational requirements of these systems. Here are some key challenges:

➢ *Intermittency and Variability:*

Power generation by renewable sources, like wind and solar, may fluctuate because of their inherent intermittent and variable nature. This makes it challenging to maintain s Table operation of electrical machines, requiring robust control strategies to handle these variations[27].

➢ *Integration with the Grid:*

Synchronizing renewable energy systems with the electrical grid is complex, especially with fluctuating supply and demand. Electrical machines need precise control to manage power quality, voltage stability, and frequency regulation [28].

➢ *Nonlinear Dynamics:*

Electrical machines, particularly inverters and converters, exhibit nonlinear behavior. Controlling these dynamics effectively requires advanced control techniques like adaptive control, fuzzy logic, or neural networks, which can increase system complexity.

➢ *Fault Tolerance and Reliability:*

Ensuring fault tolerance in the control of electrical machines is crucial, as faults can lead to system instability or damage. Renewable systems require robust controllers that can quickly respond to and recover from faults, which is challenging in a variable environment [29].

➢ *Harmonics and Power Quality Issues:*

Renewable energy systems, especially those using power electronic interfaces, can introduce harmonics into the power system. Controlling electrical machines to minimize harmonics and maintain power quality is essential but challenging due to the interaction of multiple sources and loads [30].

➢ *Efficiency Optimization:*

Maximizing the efficiency of electrical machines while dealing with fluctuating input conditions requires sophisticated control algorithms. This includes managing reactive power, optimizing the power factor, and dynamically adjusting operating points [31].

➢ *Thermal Management:*

Electrical machines in renewable energy applications, like wind turbines or solar inverters, are exposed to varying thermal conditions. Effective thermal management through control systems is necessary to prevent overheating and ensure longevity, posing an additional layer of complexity [32].

➢ *Scalability and Modularity:*

As renewable energy systems scale up, controlling a large number of distributed electrical machines becomes more complex. Developing scalable control strategies that maintain performance across different scales and configurations is a significant challenge.

➢ *Real-time Control and Monitoring:*

A need for real-time monitoring and control to handle dynamic changes in renewable energy inputs requires fast and reliable communication networks and control algorithms, which can be difficult to implement in remote or large-scale systems [33].

➢ *Cost Constraints:*

Implementing advanced control techniques often involves high costs due to the need for sophisticated sensors, processors, and communication systems. Balancing cost-effectiveness with the need for robust control remains a challenge.

VII. LITERATURE REVIEW

The majority of prior research on robust control of electrical machines in renewable energy systems has employed statistical techniques.

In Al-Saddaee, Azzawi and Ari, (2023), pursues the analysis and simulation of a hybrid energy management system that employs dependable management strategies and draws energy from several sources to provide loads with appropriate levels of energy. The power sources are hybrid, so we can use two of them in backup mode simultaneously, which is great for our power needs. A primary objective of this research project's design is to maximize an utilization of different power sources via the use of certain techniques, technical processes, and systems. The goal of developing and implementing an MPPT-

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based fuzzy logic controller is to reliably and effectively extract a maximum amount of power possible by the source[34].

In Wang, Lin and Hsu, (2023),recommends a DC microgrid (MG) that uses a DC/AC converter to link to a simplified Taiwan Power System. A supercapacitor-based energy storage system, electric car charging stations, and renewable energy sources would all be part of the MG. A small-signal stability of a setup under study is examined using both static and dynamic simulations[35], .

In Zhou, Xu and Huang, (2018), First, the MGP system's fundamental operating concept is described. Next, a theoretical foundation for the source-grid phase control technique is put forward. To compare PV systems with and without MGP systems, we do an experiment to measure their frequency response. The research suggests that inertia-based renewable energy sources may be supported by the MGP system, which might lead to better frequency stability in the power grid[36],.

In Rezaei et al., (2022), A linearised model of energy management is proposed to include electric vehicle parking, distributed generation, energy storage, combined heat and power, renewable energy sources, and energy into a microgrid in order to lower the operating expenses of the system. Additionally, the impact of a 40% rise in power prices on the overall cost of operations has been assessed; the findings indicate that this results in a 5.35% increase in total costs notwithstanding the increase in electricity prices[37],.

In Zhang et al., (2023), examines how OW-PMSM are used in renewable energy systems. By adjusting a relative importance of a two inverters in the OW-PMSM drive, the microgrid and energy storage may exchange power in a flexible manner. The PMSM in this scenario might be either a generator or a load motor. OW-PMSM may also be used in FESS for sustainable energy production. The OWPMSM regulates the machine, power producing equipment, and grid to provide flexible power supply. Using the OW-PMSM to its maximum potential in both contexts has a potential to lessen an impact of intermittent renewable power generation on system reliability[38],.

In Zhang et al., (2020), suggested using transient stability probability analysis to design the dynamic reactive power components of a renewable energy system with high penetration. First, the high penetration renewable energy grid's vulnerability is identified using a transient stability probability evaluation to enable dynamic reactive power allocation; After that, a complete evaluation of a high-penetration renewable energy system using several scenarios is needed in order to put the dynamic reactive power capacity allocation into action. Next, the method's viability is shown via the use of the IEEE 39-bus system. The findings point to the possibility that this method might influence the secure and safe functioning of renewable energy bases, increase the reliability of power grids, and lessen a likelihood of large-scale off-grid situations with a high penetration of renewables[39],.

This Table 3 summarizes methodologies and findings of each paper while identifying limitations and future research directions of the electrical machines in renewable energy systems.

Table 3 Summary of the Related Work with Key Factors

Ref	Methodology	Key Findings	Drawbacks	Future Work
[34]	Hybrid energy management system with Fuzzy Logic Controller and MPPT algorithm	Demonstrates optimal energy supply from multiple sources using fuzzy logic and MPPT; effective backup operation	Limited to specific configurations; may need broader validation	Explore integration with more diverse energy sources; refine control algorithms for wider applications
[35]	DC microgrid with RESs, EV charging stations, and SC-based ESS; steady-state and dynamic simulations	Analyzes stability and performance; DC/AC inverter connectivity to Taiwan Power System	Simulation scope may not cover all real-world scenarios	Further testing with larger and more varied grids; evaluate long-term stability and performance
[36]	Source-grid phase control method; comparison of frequency response with/without MGP system	MGP system provides inertia support, improving frequency stability	Experimental setup may not fully capture all grid dynamics	Test with different grid configurations; investigate scalability of MGP system
[37]	Linearized energy management model; includes renewable resources, storage, distributed generation	Operating cost improvement despite electricity price increase; cost increase is minimal	Model may oversimplify real-world complexities	Incorporate additional factors such as demand response; explore impact of varying market conditions
[38]	Application of OW-PMSM with dual inverters; flexible power flow and storage	Achieves flexible power delivery; stabilizes grid by handling fluctuating renewable generation	Limited to OW-PMSM configurations; potential integration challenges	Investigate other machine types and configurations; assess long-term impacts on grid stability
[39]	Dynamic reactive power configuration based on	Improves security and stability of high penetration renewable	Focused on transient stability; may not	Expand to include other grid stability aspects; apply method

	transient stability probability assessment	grids; reduces risk of large-scale off-grid events	address all stability issues	to different grid sizes and configurations

VIII. CONCLUSION AND FUTURE WORK

Renewable energy sources are becoming more and more acknowledged for their ability to provide eco-friendly and long-term substitutes for traditional energy sources. If we want to make use of renewable energy sources, we must incorporate electrical equipment into existing systems. In this article, we have looked at the several electrical devices that may be used for renewable energy, and we have also discussed their pros and cons. It has also highlighted the key challenges faced in controlling these machines, such as managing intermittency, integrating with the grid, handling nonlinear dynamics, ensuring fault tolerance, and optimizing efficiency. To address these challenges, advanced control strategies and technological innovations are essential. Solutions such as adaptive control techniques, robust fault-tolerant designs, improved thermal management systems, and cost-effective power conditioning methods are vital for improving a performance and reliability of renewable energy systems. The intricacies of large-scale renewable energy systems may be better managed with control technologies that are both scalable and flexible, which should be the focus of future research. By overcoming these challenges, the renewable energy sector can achieve greater efficiency and sustainability, contributingto a cleaner and more resilient energy future.

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