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Winds of Power: Data Analysis for the Relationship between Wind Speed, Gust, and Power Output

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***Abstract*- Wind turbines are the most cost-effective and quickly evolving renewable energy technology. Benefits of this technology include no carbon emissions, resource conservation, flexible applications, modularity, fast installation, rural power grid improvement, and potential for agricultural or industrial use. Wind turbine power analysis is a crucial aspect of wind energy production, encompassing the evaluation and optimization of wind turbine performance. Its significance stems from its role in ensuring efficient energy generation, maximizing power output, and minimizing operational costs. Wind turbine power analysis plays a pivotal role in optimizing wind energy systems, from site selection and turbine design to predictive maintenance and grid integration. By analyzing power curves, historical data, and environmental factors, engineers can identify performance faults, maximize efficiency, and ensure the long-term viability and sustainability of wind energy projects.**

***Keywords*- Wind turbine, Data analysis, Winds of Power**

I. Introduction

Energy is one of the most important industries of the present and the future. The significance of the energy industry is emphasized by some global challenges, such as the need for sustainable development and the effects of climate change. In today's world, global energy strategies need to take into account not only how to fulfill the anticipated energy needs of the future but also how to ensure the reliability of their energy supplies. In this context, a number of studies calculate the rising demand for energy, the amount of fossil fuels that are still available, and the importance of alternative resources. The International Energy Agency (IEA) forecasts that the demand for energy around the world will climb by 90 percentage points by the year 2035 if the average annual tendency for growth does not alter. Because of the rising demand for energy, substantial expenditures are needed in the generation, transmission, and distribution of power, as well as in the management of energy [1].

Wind energy has the advantages of being clean, pollution-free, and sustainable, making it a top choice among alternative energy sources [2]. Wind power is the renewable energy source with the most potential for future large-scale expansion and use, as seen by the annual increase in the global installed gross capacity of wind power shown in Fig. 1. However, the utilization rate of wind resources is still relatively low [3], as reported by the Global Wind Energy Outlook provided by the Global Wind Energy Council.

Since approximately 20–25 years ago, wind turbines have been utilized in the process of the generation of electrical power [3]. According to the statistics, the costs of operation and maintenance of wind turbines account for approximately one-fourth of the total cost of generating electricity using wind power. Wind turbines have to be able to survive severe and unforgiving environments while they are in operation. These environments create stress cycles in the components, which pushes the materials to the boundaries of their fatigue endurance [4]. In particular, rotating devices are subjected to various loading combinations, including gyroscopic loading, highly erratic wind, and gravity [5]. As a consequence of this, it is of the utmost importance, during the process of developing wind turbines, to precisely forecast and efficiently improve their service life [6]. In recent decades, the wind turbine sector has witnessed gains in reliability, although it nevertheless continues to exhibit greater failure rates in comparison to other industries [7].

The mechanical energy created by the rotation of the blades in conventional wind turbines is converted into alternating current (AC). The power of the wind is equal to the kinetic energy of the volume of air (ρ) moving over an area (A) perpendicular to the direction of the wind (V) in a certain period of time. Using Eq. (1), we can determine how much energy a wind turbine is capable of producing.

$$P = \frac{1}{2}\rho\, C_p(\lambda,\theta) A\, V^3 \quad (1)$$

The power coefficient of the turbine is represented by the symbol (C_p) function in this equation. This coefficient is determined by two parameters: the ratio of the tip speed λ to the rotor speed and the angle of the blades θ. The ratio of the tip speed to the blade speed is dependent on the values u and V in equation 2.

$$\lambda = \frac{U}{V} \quad (2)$$

Betz claims that in order to obtain the greatest amount of power from an unshrouded wind turbine, the wind speed must be slowed by one third down through the rotor. This is the only condition under which this is achievable. In that scenario, theoretic maximum power coefficient is calculated to be 0.59 [8]. Having said that, this is the best-case scenario; in reality, there are a variety of losses that should be taken into consideration. Both equations (1) and (2) demonstrate that the size of a turbine has a significant impact on the amount of power it can produce.

Wind power is an intermittent source of electricity. As a result, there are many factors to take into account when integrating large-scale wind energy production into the grid. These factors include geographical and temporal coordination, demand, response, and storage, monitoring, and control and management actions. To provide a consistent supply, storage and backup solutions are being investigated as part of numerous research and development projects [9]. In order to accommodate the expanding demand and the diverse local

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supply sources, such as smart grids, a more dependable, secure, and efficient grid is required [10]. This is because energy transmission bottlenecks may pose a threat to restrict the system's ability to expand in the future.

Analysis of the greatest power that can be extracted from PMSG-based wind turbine systems and PMVG-based wind turbine systems for comparison. In this study, a comparison is made between the performance of different wind energy conversion systems that make use of permanent magnet synchronous generators (PMSG) to extract the maximum amount of power [11]. In this study, dynamical models of PMSG and PMVG-based wind turbine systems are constructed, and their dynamical performance is validated using both classic and improved optimum torque control-based MPPT (Maximum Power Point Tracking) techniques. The research suggests a generator current augmentation-based optimal torque management method as a way to extract the maximum amount of output power from different wind conditions. This would reduce the influence of the moment of inertia and ensure that the MPPT system would operate well during transients. This article presents an analytical model of a 5-kW PMSG and PMVG-based wind turbine system in order to provide a fair comparison of MPPT schemes and to highlight the benefits and drawbacks of each one individually. PMVG shows enhanced power extraction efficiency over PMSG for typical optimum torque management, as demonstrated by comparative simulation and experimental data. These results highlight the viability of deploying both PMSG and PMVG in wind turbine systems.

Research Concerning the Modelling and Analysis of Frequency-Responsive Wind Turbines Involved in Power System Ultra-Low Frequency Oscillation is presented in [12]. A dynamic analysis of frequency-responsive wind turbines that are involved in power system ultra-low frequency oscillation is presented in this paper. DFIG wind turbines (WTs) utilized in such systems are necessitated to exhibit frequency-responsive behavior and contribute to inertia and frequency support. The paper establishes a mathematical model to comprehensively capture the dynamics of DFIG WTs that display frequency-responsive characteristics at the electromechanical timescale. Conducted on a 2-machine system, the analysis reveals the dynamic behaviors of WTs and their interference mechanism with the hydraulic generator (HG). The system ultra-LFOs encompass WTs' frequency control, speed control, MPPT control, and pitch control, albeit with distinct effects contingent upon the operating modes. Moreover, the paper conducts case studies on a modified 10 machine 39-bus New-England power system to further scrutinize the impacts of DFIG WTs on ultra-LFO damping. By virtue of the modeling endeavor and simulation studies, the paper imparts recommendations for the utilization of DFIG WTs in wind-hydropower hybrid systems to aid in the attenuation of the ultra-LFO.

Analysis of the Power Output and Response of a Semi-Submersible Wind Turbine Using Combined Flap Type and Torus Wave Energy Converters is proposed in [13]. A power analysis of a semi-submersible wind turbine that combines flap type and torus wave energy converters is presented in this paper. The examination centers its attention on the interaction amidst the wind turbine and the wave energy converters. The evaluation of the power performance of the wind turbine is conducted across varying wave conditions. Additionally, an analysis is undertaken to comprehend the reaction of the wind turbine to loads instigated by waves. When compared to a wind turbine operating independently, the combined system exhibits enhanced power performance. The wave energy converters make a substantial contribution towards the overall power generation of the system. By means of the response analysis, valuable insights are gained into the structural conduct and load distribution of the wind turbine in the presence of wave-induced forces.

Analysis of the effect of leading-edge protection on the performance between wind turbines using methodologies based on the breakdown of energy and power is suggested in [14]. This study presents an energy decomposition methodology as a method for analyzing the power production efficiency of wind turbines. More specifically, the study focuses on the impact that leading-edge protection has on blade reliability. The focal point of the investigation centers around the influence of cutting-edge preservation on the energy and power generation of wind turbines. Approaches to decompose energy are employed to scrutinize the dissemination of energy within the wind turbine system. Approaches to decompose power are employed to scrutinize the generation of power and the effectiveness of the wind turbine. The analysis offers valuable insights into the efficacy of cutting-edge preservation in enhancing the performance of wind turbines. The outcomes of the investigation can be utilized to optimize the design and operation of wind turbines equipped with cutting-edge preservation.

The mechanical design and power analysis of a modified drive train system for a Type-III wind turbine are the primary topics of this particular piece of research [15]. The mechanical drive train system is vital to wind power generation, especially during rapid wind speed changes. The research recommends modifying the mechanical drive train system to handle wind speed-induced voltage sag and swell. Pitch control, gear box, and yaw are the key wind turbine components to modify. The gear box for the rotor causes slow motion during low wind speeds, so the article designs a redesigned rotor control for a Type-III wind turbine. Comparing the improved rotor system to previous models, the paper shows how it can help reactive power regulation. MATLAB/Simulink is used to develop and validate the improved drive train system, with CFD analysis.

This article examines the relationship between the power characteristics of wind turbines and the total amount of energy generated [16]. In this study, a variety of approaches and controllers that are utilized for maximum power point tracking (MPPT) in WECS are analyzed and compared. These approaches and controllers include tip speed ratio (TSR), fuzzy logic control (FLC), incremental conductance (INC), perturb and observe (P&O), and cuckoo search algorithm (CSA). The performance of permanent magnet synchronous generator (PMSG) and permanent magnet vernier generator (PMVG)-based wind turbine systems (WTS) that use MPPT control technology is analyzed and compared in this work.

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This study aims to provide a thorough analysis of the effects of icing on wind turbine blades and its subsequent impact on power loss in cold regions. This study examines the influence of blade icing on power reduction in a 15 MW wind turbine, revealing a substantial decline in power generation as a result of ice [17]. This study's primary objective is to gain a better knowledge of how icing affects the operation and efficiency of wind turbines in environments characterized by low temperatures. When determining the level of power loss caused by icing, several parameters like ice accretion patterns, ice thickness, and processes for ice shedding are taken into consideration. The research studies a variety of approaches and technology, such as ice detection systems, de-icing procedures, and adjustments to the blade design, with the goal of mitigating the negative effects that icing has on the operation of wind turbines. The findings of the study provide useful insights that can be used to optimize the operation and maintenance of wind turbines in cold climates, with the goal of minimizing power loss caused by icing.

This study focuses on the probabilistic and reliability analysis of an intelligent power control system for wind turbine systems that utilize a Doubly Fed Induction Generator (DFIG). This research presents an investigation of the dependability of an Artificial Neural Network (ANN) [18] control system for a wind turbine [19]. The purpose of this study is to evaluate the performance and dependability of the power control system throughout a wide range of possible operating conditions and degrees of uncertainty. The research makes use of probabilistic modeling and analysis methodologies in order to evaluate the effectiveness of the system in terms of its output of electricity, its stability, and its integration with the grid. The purpose of doing a reliability analysis is to evaluate the capacity of the system to keep its operation at its optimum level and to reduce the likelihood of any potential breakdowns or disruptions. The findings of the study contribute to the development of dependable and effective wind energy conversion systems by providing insights into the effectiveness and robustness of the intelligent power control system for DFIG-based wind turbine systems [20].

II. Dataset Description

The dataset contains data collected from a wind turbine's SCADA (Supervisory Control and Data Acquisition) system in Turkey. The SCADA system measures and records various parameters at 10-minute intervals. The dataset provides insights into the performance and operational characteristics of the wind turbine, including power generation, wind speed, wind direction, and theoretical power values. The dataset contents are as follows: (i) Date/Time: The timestamp indicates the time and date of the data recording at 10-minute intervals. (ii) LV Active Power (kW): The active power generated by the wind turbine at each recording point, measured in kilowatts (kW). (iii) Wind Speed (m/s): The wind speed at the hub height of the wind turbine, measured in meters per second (m/s). It represents the wind speed used by the turbine for electricity generation. (iv) Theoretical Power Curve (kWh): The theoretical power values that the wind turbine is expected to generate at a specific wind speed. These values are provided by the turbine manufacturer and are measured in kilowatt-hours (kWh). (v) Wind Direction (°): The wind direction at the hub height of the wind turbine, measured in degrees (°). Wind turbines are designed to automatically align themselves with the wind direction. The main objective of this dataset is to analyze and understand the relationship between wind speed, wind direction, and power generation in a wind turbine. It provides an opportunity to explore the turbine's performance, evaluate its efficiency, and compare the actual power generation with the theoretical power values provided by the manufacturer.

III. Wind Turbine Power Analysis

The Wind Turbines SCADA Systems data can be used for wind turbine data analysis. It provides valuable information on various parameters such as power generation, wind speed, wind direction, and theoretical power values. Some of the potential analyses and applications may be as follows:

(i) Performance Analysis: it can analyze the relationship between wind speed and power generation to assess the turbine's performance. This analysis can help identify efficiency improvements, evaluate the turbine's capacity factor, and optimize power output.

(ii) Power Curve Validation: By comparing the actual power generation with the theoretical power values provided by the manufacturer, it can validate the accuracy of the turbine's power curve. This analysis helps assess the turbine's performance against expected values and identify any deviations or discrepancies.

(iii) Anomaly Detection: By analyzing the data for unexpected patterns or outliers, it can detect anomalies or abnormal behavior in the turbine's performance. This analysis can help identify potential faults, malfunctions, or operational issues that may require attention or maintenance.

(iv) Wind Resource Assessment: The data provides wind speed and wind direction data, which can be used for wind resource assessment. it can analyze the wind characteristics at the turbine's hub height to evaluate the site's wind potential and suitability for wind energy projects.

(v) Predictive Modeling: Using machine learning techniques, it can develop predictive models to estimate power generation based on wind speed and wind direction. These models can help forecast power output, optimize turbine operation, and support energy management decisions.

(vi) Operational Optimization: By analyzing the data, you can identify patterns and trends in wind speed, wind direction, and power generation. This analysis can help optimize turbine operation, such as determining the most favorable operating conditions based on wind characteristics and adjusting the turbine's orientation to maximize power output.

(vii) Comparative Analysis: You can compare the performance of multiple wind turbines or wind farms using this dataset. By analyzing the data from different turbines or locations, you can identify variations in performance, assess the impact of environmental factors, and benchmark performance against industry standards.

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Figure 1 represents a bar graph that compares the theoretical power curve and the actual power curve of a wind farm. The graph displays two sets of vertical bars representing different power values based on the wind direction. The x-axis represents the "Wind Direction," while the y-axis represents the "Power" measured in kilowatts (kW).

The "Theoretical Power Curve" indicates the expected power values generated by the wind turbines for each specific wind direction. The "Actual Power Curve" depicts the real-time power values generated by the wind farm for each wind direction. The figure aims to compare the expected power generation (theoretical) with the actual power output (measured). It provides insights into how well the wind farm performs in terms of power generation efficiency and how closely it aligns with the expected theoretical values. By visually comparing the two sets of bars, it becomes possible to identify any discrepancies or variations between the

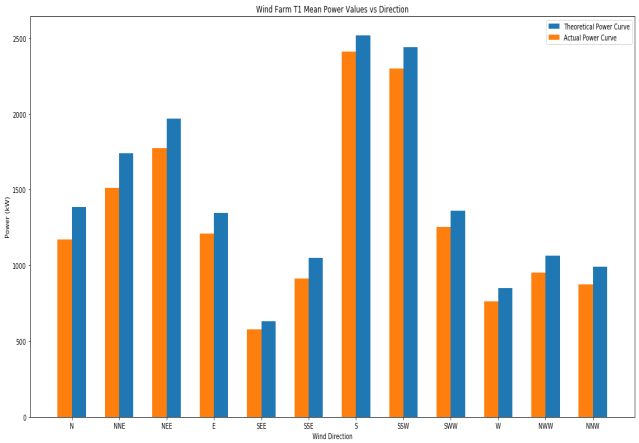

Figure 1. Wind Farm Mean Power Values vs Direction

theoretical power curve and the actual power curve of the wind farm.

Figure 2 compares the total energy generation values according to different wind directions in a wind farm. The "Theoretical Power Curve" indicates the expected total energy generation values generated by the wind turbines for each specific wind direction. The "Actual Power Curve" depicts the

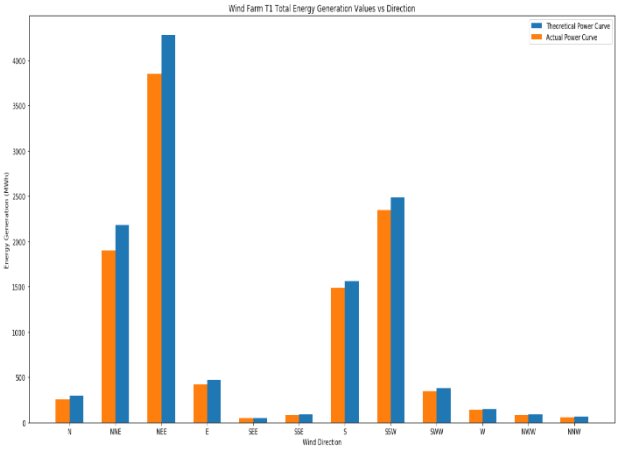

Figure 2. Wind Farm Total Energy Generation Values vs Direction

real-time total energy generation values achieved by the wind farm for each wind direction. The figure aims to compare the expected total energy generation (theoretical) with the actual total energy generation (measured) in the wind farm. It provides insights into how well the wind farm performs in terms of overall energy generation and how closely it aligns with the expected theoretical values.

Figure 3 represents the total loss values associated with different wind directions in a wind farm. The figure features a set of vertical bars that depict the total loss values for each specific wind direction. The "Wind Direction" and the "Total Loss" are measured in megawatt-hours (MWh). This figure aims to visualize the extent of energy loss occurring for different wind directions in the wind farm. It highlights the inefficiencies or factors contributing to the reduced energy generation within specific directional ranges. Analyzing the distribution can help identify areas or wind directions where the energy loss is more significant, allowing for targeted

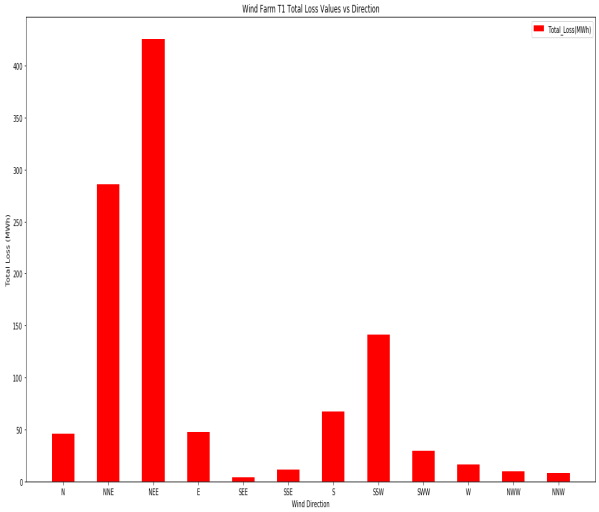

Figure 3. Wind Farm Total Loss Values vs Direction

improvements or adjustments to maximize energy generation.

Figure 4 represents a power curve graph for a specific turbine in a wind farm. The figure showcases two curves:

1. *Theoretical Power Curve:* This curve represents the expected or theoretical power generation of the turbine at different wind speeds.

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2. *Actual Power Curve*: This curve represents the actual power generation of the turbine at different wind speeds. The "Wind Speed" is measured in meters per second (m/s), and the "Theoretical Power" is measured in kilowatts (kW).

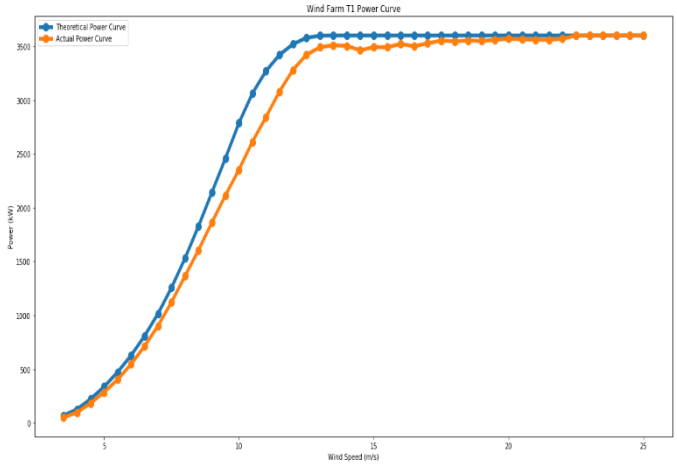

Figure 4. Wind Farm Power Curve

The power curves allow comparing the theoretical power generation of the turbine with its actual power generation at varying wind speeds. By observing the relationship between the two curves, they can assess the turbine's performance in terms of efficiency and power output.

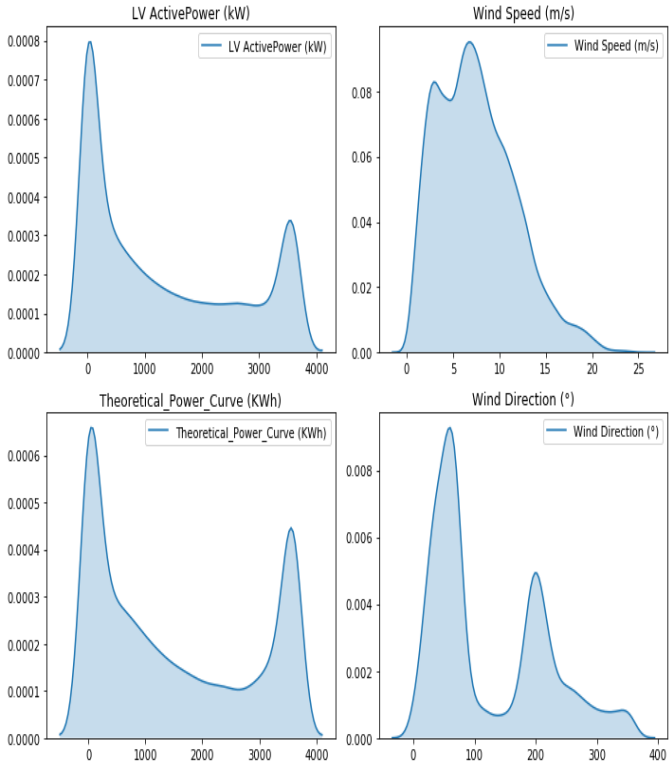

Figure 5. kernel density estimation

A grid of subplots is presented in Figure 5, the data distribution using kernel density estimation (KDE) plots for each column in the dataset. Each subplot represents the KDE plot for a specific column of the dataset. KDE plots are useful for understanding the shape and distribution of data, offering insights into its central tendency, skewness, and the presence of multiple modes or peaks. By examining the KDE plots for each column in the dataset, you can gain a better understanding of the underlying data distribution.

Figure 6 illustrates a wind rose graph. A wind rose graph visualizes the distribution of wind direction and speed. The circular plot is divided into sectors, each representing a range of wind directions, while the length of the bar within each sector corresponds to the frequency or intensity of wind speeds falling within that direction range.

Figure 7 represents a basic line plot. A line represents the relationship between wind speed and power. This line represents the relationship between gust and power. The line plot visualizes the relationship between wind speed, gust, and power. Each point on the plot represents a specific wind speed or gust value and its corresponding power value. By examining the lines, you can analyze how power output changes with different wind speeds and gusts.

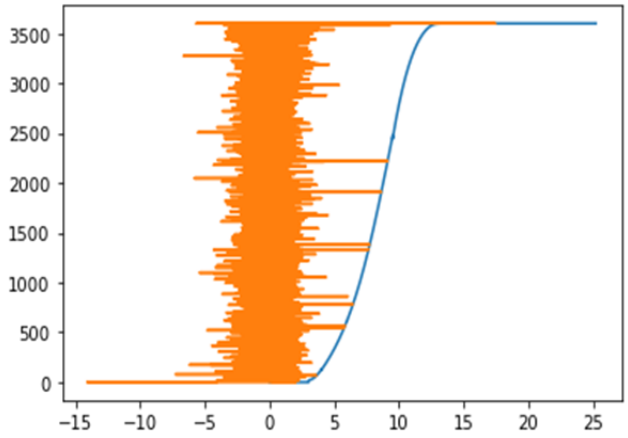

Figure 7. A basic line plots

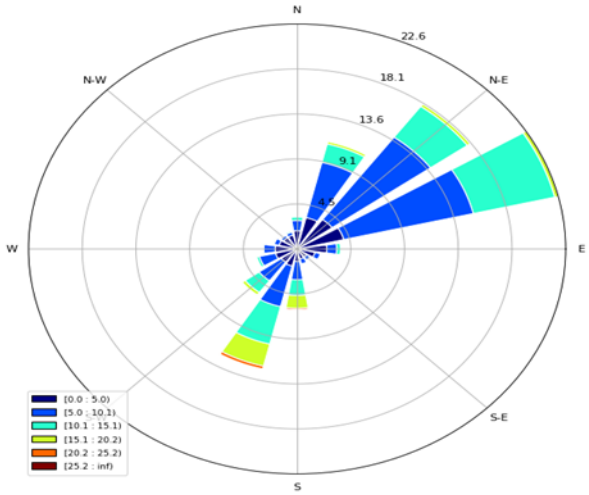

Figure 6. a wind rose graph

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CONCLUSION

In conclusion, this manuscript highlights the significant potential of wind energy as a clean and sustainable power source. It emphasizes the importance of ongoing research and development efforts in optimizing wind turbine technology, grid integration, and operational efficiency. By addressing key challenges such as power generation optimization, grid reliability, and environmental considerations, the wind energy industry can play a vital role in addressing global energy and climate challenges.

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