Prediction of wind power with various air speed using neuro-fuzzy logic in MATLAB

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ABSTRACT

The energy crisis in Bangladesh has persisted for many years, predominantly reliant on fossil fuels for power generation, which is both economically and environmentally costly. It is imperative to transition away from fossil fuels towards more cost-effective and eco-friendly energy sources. Wind energy presents a viable solution to alleviate this crisis, especially considering Bangladesh's extensive coastline, offering great potential for harnessing significant amounts of electricity. Extensive fepresearch has been conducted on the feasibility of deploying wind turbines across various coastal zones to generate power and facilitate irrigation seasons. This research delves into the operational principles and performance parameters of wind turbines. A modified fan is utilized to assess power generation under varying air speeds, with data analysis conducted using neuro-fuzzy logic. The findings reveal a minimal percentage error of 0.09, underscoring the reliability of the proposed fuzzy model in predicting wind power output based on wind speed. This underscores the potential for leveraging wind energy as a sustainable and reliable alternative to fossil fuels in addressing Bangladesh's energy challenges.

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1. INTRODUCTION

Although Bangladesh is an agriculture-based country but in recent years it has huge investment in small and medium level industry. For growing industrialization and urbanization, electricity demand is increasing very fast. The government has introduced some short-term leasing programs that mostly rely on diesel and furnace oil. Since most of the power station is using natural gas, so certainly there is a shortage of gas supply which affects the electricity production seriously. But this initiative is very costly and the government has to give huge subsidies. Aside from that, Kaptai has a small hydroelectric power plant with a 230 MW capacity. Moreover, it has 232 rivers whose flow rate is suitable for hydro-electric power generation in some extent [1]. In the current situation, Bangladesh needs to switch to renewable energy for a power solution. Wind is one of the great sources that can be used to yield renewable energy. Bangladesh is located between 20.34- and 26.38-degrees north latitude and 88.01- and 92.41-degrees east latitude. It has a coastline of almost 724 kilometers [2]. It has already been discovered that modest wind turbines can be installed in coastal areas. Both cost analysis and technological benefits are needed for the investment in this sector. Muhuri Dam, Feni, of 0.99 MW, and Maheshkhali of 2 MW wind power plants are established here. During the irrigation period, wind energy can be utilized for irrigation, that will be helpful for reducing energy crisis, especially in rural areas. However, this method considered the expenses that were higher than the actual expenditures. Wind power is the second most affordable source of electricity in Bangladesh, with a cost estimate of BDT 6 per kWh, coming after natural gas, which costs BDT 3 per kWh [3]. Bangladesh has a wind energy potential of around 20,000 MW, with a wind speed of less than 7 meters per second. Wind energy research in Bangladesh is started some years back, and it has already demonstrated that certain of Bangladesh's southern areas have a lot of potential for wind energy [4], [5]. Wind power energy can reduce the dependence on fossil fuel [6]. Wind energy can play a vital role in abating the energy crisis [7]. Wind is an excellent and cost-effective source of renewable energy. Bangladesh, with its extensive coastline, experiences consistent wind year-round. This makes it an ideal location for harnessing wind energy, as it benefits from various wind patterns throughout the year [8]. The analysis presented in this paper indicates that a mix of renewable energy, coal, and uranium is the most effective option for large-capacity power plants in Bangladesh to meet the country's electricity demand [9]. The thrust increases as the wind velocity increases, but decreases as the pitch angle increases. There is an ideal pitch angle for a given wind velocity at which the turbine generates the most power. The stall characteristics of the airfoil blade have been linked to the effect of pitch angle on the power produced [10].

In recent years, the energy demand of Bangladesh has increased significantly for its expanding economic development and population size [11]. From March to September, this wind blows at a speed of 3 to 6 m/s over the surface of Bangladesh. Wind speed is often lower from October to February. In June-July, the maximum wind speed is reached. Putting up wind turbines along the coast could be a better way to help the national grid. Aside from these locations, Bangladesh has many mountainous zones and remote islands where wind flows at a constant speed of 2 to 5 m/s throughout the year [12]. Bangladesh can get 650 MW of energy from a coastal area through wind power [13]. For a long coastal area, it produces a significant amount of electricity for agricultural production [14]. Based on the wind power density (WPD) and the mapped rotor diameter of turbines for different wind power classes, it has been determined that large-scale wind turbines are viable in Chittagong and Jessore, medium-scale turbines in Khepupara, and small-scale turbines in Cox's Bazar and Hatiya [15]. In the present day, to measure the potentiality of wind power neuro-fuzzy logic system is used since this system has a good accuracy for prediction [16]. Shao *et al*. [17] stated in their research presented a new wind turbine control strategy that involves using a PID controller and particle swarm optimization to control the pitch angle, which must be regulated to capture the maximum amount of power. Due to its advanced capabilities compared to other deep learning and statistical models, the gated recurrent unit (GRU) model is well-suited for predicting wind turbine output power [18].

The results produced by the fuzzy-based technique are very similar to the calculated values when compared to those obtained using the model predictive-based technique [19]. The adaptive fuzzy logic controller (AFLC) method is widely favored due to its rapid response and superior performance compared to traditional fuzzy logic controller (FLC) and perturb and observe (P&O) strategies [20]. Wind power site selection is also an important factor in getting optimum power from the wind turbine. Wind power can contribute a good role in the power generation process in Bangladesh. Now a hybrid wind solar power system is becoming a popular scheme throughout the world. Subsequently, the hybrid power is a very lucrative power model that is very suitable in the coastal areas of Bangladesh [21]-[25].

Wind energy optimization is very challenging in the present world. So, power generation by wind should be analyzed in a deep manner of concern. From this aspect, this research study has been carried out. This paper has initiated the experiment set up for the wind power system in a small scale to observe the power performance. To investigate the forecasting of wind power, a series of data has been obtained from the practical set up. In addition, for forecasting the wind power, a fuzzy logic algorithm has been implemented in MATLAB Simulink environment. Finally, a brief data analysis has been presented in this paper showing the accuracy of forecasting through graphical analysis.

2. METHODOLOGY

A modified fan is connected to a DC motor, and established the connection to the load using a multimeter. Data has been measured using an anemometer while connected to a wind source. Data has been input into MATLAB and employed a neuro-fuzzy logic system during simulation. Finally, outcomes have been evaluated and put into practice. A voltage controller, shown in Figure 1 is a device or system used to regulate and control the voltage levels in an electrical circuit. It is designed to maintain a stable and desired voltage output despite fluctuations in the input voltage.

Data has been taken from a multimeter every time as generated in DC output voltage, output current, and air speed by anemometer as input, and calculated power output. The ANFIS model is given as Figure 2. An adaptive neuro-fuzzy inference system (ANFIS) shown in Figure 2, is a computational model that combines the strengths of artificial neural networks and fuzzy logic to perform various purposes, including pattern recognition, prediction, and system control. ANFIS employs a fuzzy inference system that adapts and learns from data, allowing it to model complex relationships between inputs and outputs.

A membership function input diagram shown in Figure 3 is a graphical representation used in fuzzy logic systems to illustrate how numerical input values are translated into linguistic terms or fuzzy sets. It displays the input variables on the horizontal axis, showcasing the entire range of possible values for a given parameter. These values are then associated with various linguistic terms or fuzzy sets. Each linguistic set is represented by a membership function, typically depicted as curves or shapes. A membership function output diagram is a visual tool in fuzzy logic systems that illustrates how fuzzy output values, represented as linguistic terms or fuzzy sets, are converted into crisp or numerical values. Output variables are displayed on a horizontal axis, with each linguistic term linked to a specific membership function. This diagram aids in understanding the transformation of fuzzy results into precise numerical values, making it essential for decision-making and control systems in various applications. We get the input and output structure from our model.

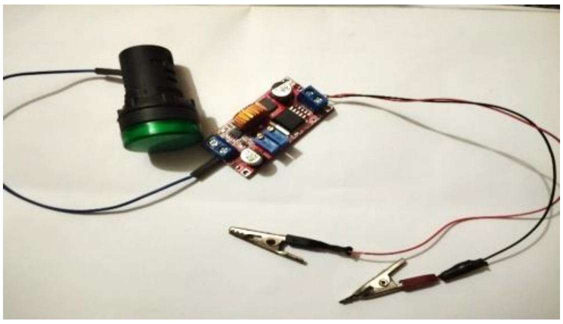

Figure 1. Voltage controller with LED

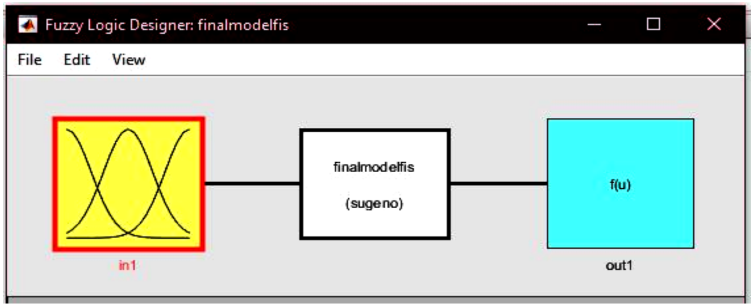

Figure 2. Proposed model

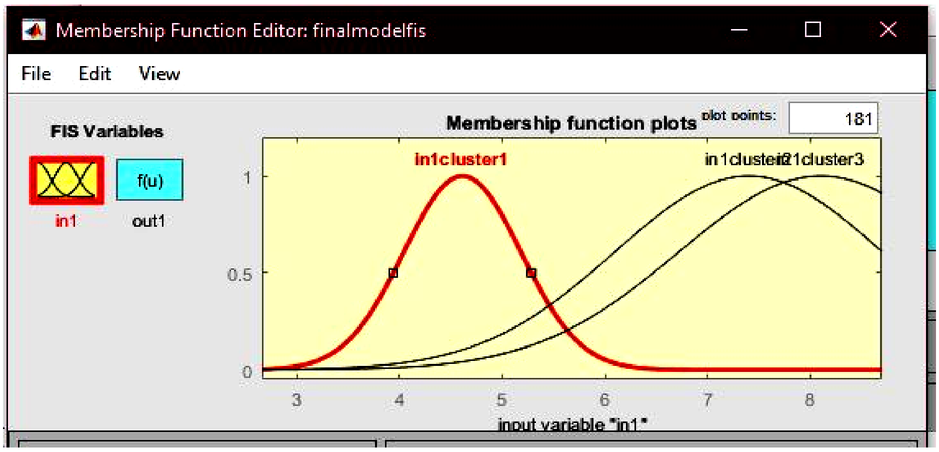

Figure 3. MF diagram (input)

A structural diagram of an adaptive neuro-fuzzy inference system (ANFIS) shown in Figure 4 outlines the key components of this hybrid computational model. It typically includes an input layer for numerical data, a fuzzification layer to convert inputs into fuzzy values, a rule layer that computes rule firing strengths, a consequent layer to determine output values, a normalization layer to adjust outputs, and an output layer for the final numerical result. ANFIS can vary in complexity depending on the problem, and its structural diagram illustrates how it combines neural networks and fuzzy logic to make decisions based on both quantitative and qualitative data.

Some data from our data are used as testing data and the rest data as training data. Figure 5 represents the training data error. It is noticed that some errors in the testing data which in about 0 to 6% which is shown in Figure 6. To find out the error, the training and testing data are added first. Then training data and finally testing the data. It is seen in the diagram below. Where the blue dots are the measured average power data and the red dots are our true average power of our testing data. After using neuro fuzzy logic system on training and testing data, the following diagram is obtained.

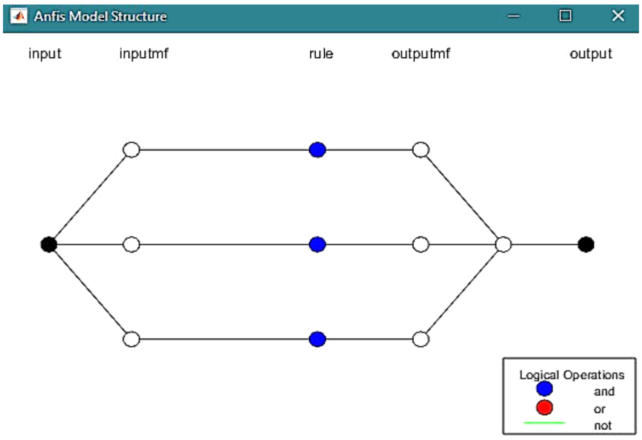

Figure 4. Structural diagram

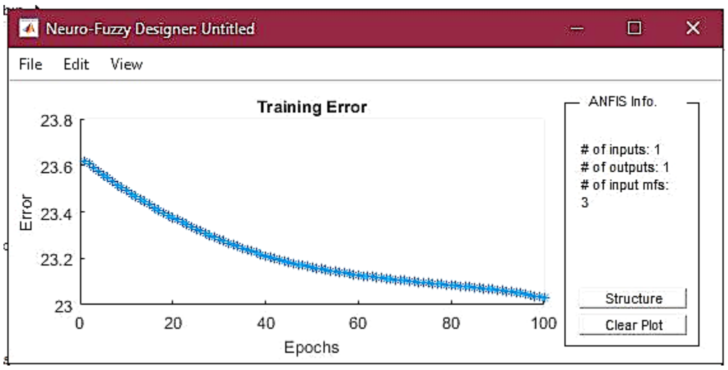

Figure 5. Training data error

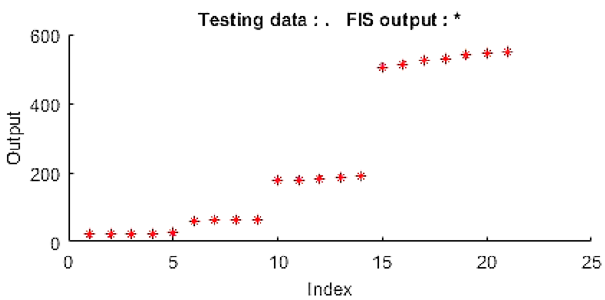

Figure 6. Testing data error

A rule layer in an ANFIS model shown in Figure 7 is a crucial component responsible for generating fuzzy rules and their corresponding membership grades. It takes the input data and processes it through a set of fuzzy if-then rules, each with its associated membership functions, and provides an output. These rules help in capturing the underlying relationships of the input variables and the output.

A "surface view" in the context of ANFIS typically refers to a graphical representation or visualization of the ANFIS model's output as it relates to two input variables. A surface view is created by plotting the model's output as a three-dimensional surface. The two input variables are typically plotted on the x and y axes, and the ANFIS output (or the model's predictions) is represented as the z-axis or the height of the surface as shown in Figure 8.

Statistical analysis conducted to establish the relationship between wind speed and power output, and calibrate a predictive model in MATLAB for real-time power forecasts. This model is continuously monitored and adjusted for accuracy, aiding in the optimization of the operation. Regular updates and maintenance ensure the model remains effective, contributing to efficient wind energy generation and reliable electricity production. The current and voltage by multimeter and air speed by anemometer is noted.

Figure 9 shows the experimental set up for taking the practical data for analysis through fuzzy logic model created in MATLAB. Training data and testing sets are split to assess the model's accuracy. Fine-tune the model parameters for optimal performance. Finally, when predicting wind power for future periods, obtain real-time wind speed data and feed it into the trained model to estimate the power output. Regularly update and retrain the model to account for changing conditions and improve prediction accuracy over time.

Anemometer has been used to observe the wind speed. This wind speed has been varied gradually and respective power generation by the motor has been recorded. In this way, a data set has been obtained from the practical set up. This data set has been incorporated in the MATLAB Simulink model to predict the power for various wind speed. Fuzzy logic controller has been utilized in the data prediction strategy. Furthermore, the fuzzy rules have been created by artificial intelligence network profile. Finally, the comparison of predicted and test data has been presented at the end of this paper.

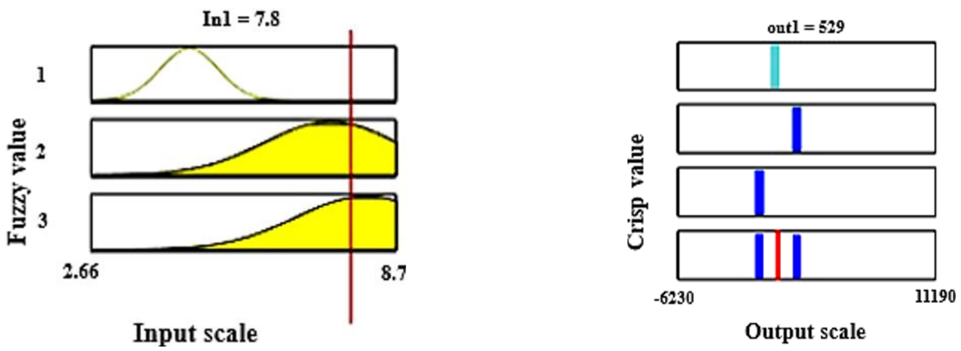

Figure 7. Diagram of average measured power in MATLAB

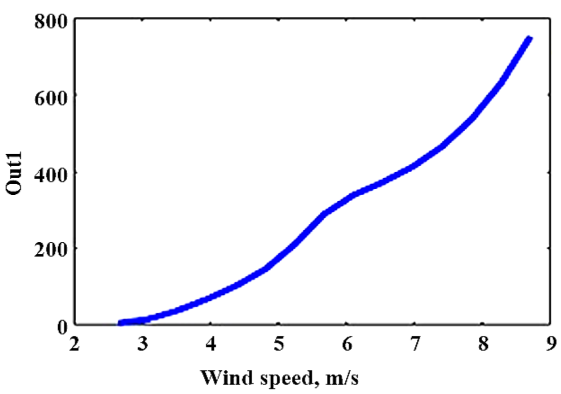

Figure 8. Average measured power (surface view)

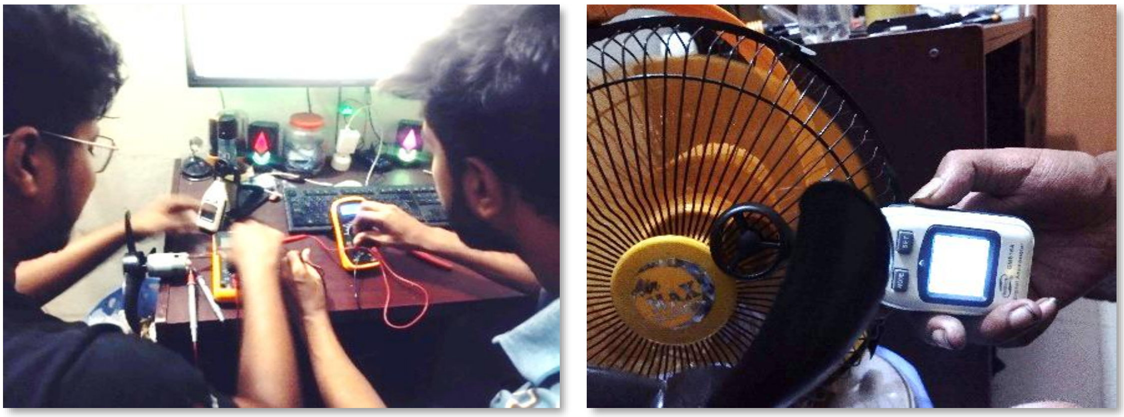

Figure 9. Practical setup

3. RESULTS AND DISCUSSION

Firstly, the power source is connected with the motor. Then it is connected with the load and an ammeter in series and a voltmeter in parallel with the motor and load. Then we took the data by placing various air speeds. As the wind speed changes, different values are obtained each time. Experimental data shows the values of current, voltage, and power of various wind or air speed found at the experiment. The maximum power is 780.84 mW if the speed is 8.7 m/s. Here, the minimum power we got 4.5 mW when the speed is 2.3 m/s. We have taken a total 179 data out of 200 sample data as training data in ANFIS. Average true power is calculated using neuro fuzzy logic system. Then the following formula has been used to find the error of testing and some training data.

Error = [(Average True Power-Average Measured Power)/Average True Power]*100%

Table 1 shows the percentage error of all the testing data from lowest to highest. Error is minimum 0.09% for air speed 7.77 m/s and maximum 6.50% when speed is 3.15 m/s. We calculate error comparing two output power by ANFIS in MATLAB neuro-fuzzy logic system. These data are used as testing data (21) to the rest (179) training data. The practical data and ANFIS Simulink are almost same and percentage of error is negligible as shown in Figure 10. This figure shows that the prediction performance has been successfully carried out by the ANFIS predicting model.

Table 1. Testing data with percentage error (%)

SL No	Input (air speed) in (m/s)	Output (true power) practical in mW	Output (measured power in mW) by ANFIS Simulink	Percentage error (%) by calculating output
1	3.15	16.15	17.2	6.50
2	3.18	17.4	18.5	6.32
3	3.19	18.9	20	5.82
4	3.19	19.32	20	3.51
5	3.22	20.46	21.4	4.64
6	3.85	60.4	60.2	0.33
7	3.87	62.73	61.6	1.80
8	3.91	63.14	64.5	2.15
9	3.93	65.52	66	0.73
10	5.02	180	174	3.33
11	5.04	183.96	177	3.78
12	5.06	186.944	180	3.71
13	5.08	190.18	183	3.77
14	5.11	193.214	187	3.21
15	7.66	515	505	1.94
16	7.69	520.38	510	1.99
17	7.77	524.51	524	0.09
18	7.8	531.2	529	0.41
19	7.85	535.04	539	0.74
20	7.88	541.8	545	0.59
21	7.9	545.67	548	0.43

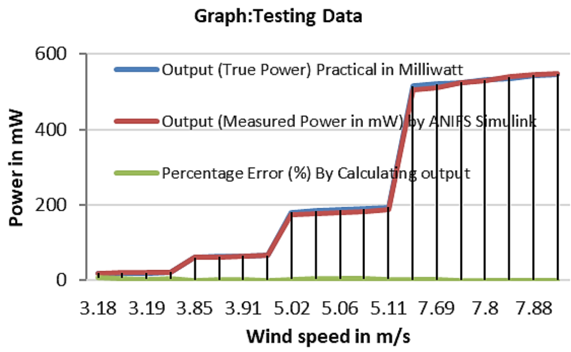

Figure 10. Testing data graph

4. CONCLUSION

The research entails the development of a MATLAB-based adaptive neuro-fuzzy inference system (ANFIS) model for predicting wind power output under varying air speeds. This process involves two main phases: training and testing. During the training phase, practical data is utilized to establish the intricate relationship between air speeds and wind power generation. The ANFIS model is trained and tested using data from the provided table to evaluate its performance. The analysis reveals a percentage error ranging from 0.09% to 6.5% during testing, indicating a reasonably accurate prediction capability. Notably, the testing phase demonstrates an inverse relationship between air speed and prediction error, with error decreasing as air speed increases. The close alignment between the measured power by MATLAB and practical values during the training phase allows the model to adapt its parameters effectively, enhancing prediction accuracy. The testing phase serves to assess the model's generalization ability by evaluating its performance on unseen scenarios. Experimental results indicate the generation of approximately 1 watt DC output, with the ANFIS model successfully predicting wind power for various air speeds. For instance, the maximum power output of 780.84 mW is observed at an air speed of 8.7 m/s, while the minimum power output of 4.5 mW occurs at an air speed of 2.3 m/s. These findings highlight the effectiveness of the ANFIS model in accurately predicting wind power output across different environmental conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

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Md. Tanvir Ahmed Shuvo		✓	✓	✓		✓	✓	✓	✓	✓			✓	✓
Dilip Kumar Das					✓				✓	✓	✓			✓
Suman Chowdhury	✓	✓	✓	✓	✓	✓	✓			✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

We authors are declaring that there is no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [SC]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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