EasyChair Preprint

№ 7291

Wind Energy Generation

A. Ambikapathy, Anna Sharma, Lakshya Varshney,
Manav Chaturvedi and Chandan Kumar

January 5, 2022

WIND ENERGY GENERATION

A. Ambikapathy[1], Anna Sharma[2], Lakshya Varshney[3], Manav Chaturvedi[4] and Chandan Kumar[5]

[a]ami_ty21@yahoo.com
[b]sharmareyansh1234@gmail.com
[c]lakshyavarshney987@gmail.com
[d]manavchaturvedi807@gmail.com
[e]Chandan.kumar1@galgotiacollege.edu

[1]*EEE Department, GCET, Greater Noida, U.P, 201306, India*
[2]*EEE Department, GCET, Greater Noida, U.P, 201306, India*
[3]*EEE Department, GCET, Greater Noida, U.P, 201306, India*
[4]*EEE Department, GCET, Greater Noida, U.P, 201306, India*
[5]*EEE Department, GCET, Greater Noida, U.P, 201306, India*

ABSTRACT-
Clean, safe, and renewable electricity is provided by wind energy, making it one of the fastest-growing green technologies. Research into sustainable power harvesting using wind resources and the ways in which wind power can be generated provides insights into the available methodologies.

A detailed overview of wind energy generation and calculation is discussed with the existing wind power production techniques.

Index Terms- **Wind Energy Generation, Wind Turbine, Power Curve, Wind Power Calculation**

I. INTRODUCTION

Having limited fossil energy resources on Earth, like coal, gas, and oil, is common knowledge. Electricity is increasingly generated from renewable sources throughout the world. The process of manufacturing solar panels uses many chemicals and resources that are harmful to the environment. Wind energy is far cleaner and cheaper than solar energy.

Using conventional energy sources such as petroleum, coal, and natural gas excessively is causing increased emissions of carbon dioxide and other harmful gases to the environment.

Global temperatures are rising at an alarming pace due to the release of harmful gases. Out of all these existing energy sources, the wind is one of the most valuable and reliable sources of energy.

With the growth of population and development, it is estimated that the energy demand may grow by 3% at the end of the year 2021. Global energy demand is projected to grow by 3% by the end of 2021 with population and economic growth. Power generators (PGs) powered by fuel produce 64.5% of the world's electricity.

In the year ahead, it is projected that U.S. households' electric bills will increase by 2.3%, based on data from the Energy Information Administration (EIA) cited in the paper [4]. With the current level of population, coal, oil, and fossil fuels are often limited in terms of energy production [3] due to overcrowding. The world has to keep up to 80% of our natural energy resources on earth in order to keep our global average temperature below 1.5 degrees Celsius. However, our reliance on these products is widening worldwide. Renewable energy sources must be exploited for socio-economic growth and development and are at the forefront of the global priority for climate action.

II. NEED OF RESEARCH

The technology of wind energy has substantially improved, and onshore wind energy has reached a maturity state, but offshore wind energy remains a highly complex challenge. New science and technological advances are necessary for offshore wind power systems, to increase the efficiency of the rotor, to improve the turbine has been discussed by the author in paper [7], [1]. There is a chance that this proposed research will change the way offshore wind energy is developed and improve the efficiency, reliability, and cost-effectiveness of the wind power system[9].In addition to wind resources, four specific research topics are presented, including wind farms, turbines, and support structures. We approach wind energy from a systems-level perspective. Furthermore, this research will involve interdisciplinary interaction and collaboration, both within this focus and between other.

III. GENERATION:

The kinetic energy of wind speed is used to generate electricity in wind turbines, hence, they create power. Wind direction and weather conditions are the most important factors affecting energy. .According to this assumption, wind turbines procure energy as follows:

$P_{wd}(t) = 1/2 * \rho * A_{tb} * V_s (t)^3$

where, ρ, Atb denotes the air density and area of a turbine blade, respectively, while, the symbol Vs(t) denotes the airspeed in m/s.As wind flows through the blade on the air pressure decreases on one side of the edge[6].The difference in air density between the blades two sides produces lift as well as drag. The lift forces are stronger than the drag which causes the rotor to spin. The rotor is attached with the generator either directly or via a shaft and the series of gears that accelerate the rotation and allow for a physically smaller generator.

INDIVIDUAL WIND TURBINE POWER ELECTRONIC TECHNOLOGY:

A typical WTS consists of the rotor with the turbine blades, a gearbox (which remains in direct-drive systems), an electric generator, a power electronic converter, and a transformer for energy conversion from wind to electricity. Several types of wind turbine concepts exist depending on the type of generator, speed controllability, and restriction of aerodynamic power [2]. Power electronics play a significant role in the design of these wind turbine concepts and have some different power characteristics. Since the turn of the century, the market was dominated by the concept of DFIGs with partial-scale power converters, but now, an AG or SG with full-scale converters has been introduced. Because of its power controllability, power electronics converters are gaining popularity.

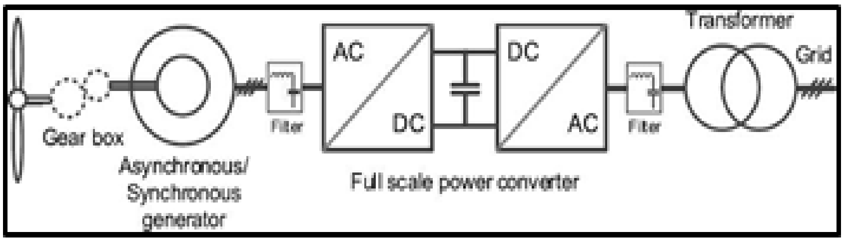

Fig.1: Wind turbine block diagram [7]

Doubly Fed Induction Generator with Partial Scale Power Electronics Converter:

DFIGs with multistage gearboxes have been adopted in the system extensively since 2000 where a multistage gearbox is used in the system [8]. Power electronics converters connected to DFIG's rotor windings are approximately 30% of the generator's power capacity. Connecting the stator windings direct to the power grid is accomplished through a transformer, and connecting the rotor windings through a transformer. The generator's rotor can be controlled by power electronics so that blade rotational speed is variable to maximize energy yield while minimizing mechanical stress. Cost-effectiveness is a chief attribute of this concept, which relies on a relatively small power converter. As described in several research papers [3], [7], its main drawback is the use of slip rings that are insufficiently reliable and insufficiently controllable under grid or generator disturbances. DFIG-based wind turbines use the two-level voltage source converter topology (2L-VSC) for power electronics conversion because the power rating requirement is relatively small[7]. This back-to-back setup is normally achievable through the use of direct current (dc) links between the two 2L-VSCs. It provides full power control and is relatively simple, despite operating in four quadrants [4].

Asynchronous/Synchronous Generator With Full-Scale Power Converter:

(a) The SCIG, excited synchronous generator (DMESG), and permanent magnet synchronous generators (PMSG) have been reported as possible solutions. Through the introduction of a full-scale power electronics converter and transforme that interfaces the grid with the generator electrical stator windings, the generated power from wind turbines can be fully regulated [4]. In comparison to the DFIG-based concept, the main advantages can be identified..

(b) Onshore wind turbines built after this concept was introduced are not always used due to more stressed power electronics components and higher power losses in the converter stage can be seen in fig 2.

(c) Because the power electronics converter in this concept needs to withstand all of the generated power at multiple megawatts, the 2L-VSC topology may suffer from a high loss at this power level.Additionally, the cabling for low voltage and high current levels below 1 kV is challenging. To improve power capacity, there are multicell converter configurations (which connect two L-VSC cells in parallel). It is noted that the wire connections on the generator side and dc-link could be different. The multicell converter configuration is a state-of-the-art solution for wind turbine products above 3 MW, since it combines standard and proven low voltage converter technologies with redundant and modular characteristics.

This conversion of aerodynamic force to the rotation of a generator creates electricity [10] can be seen in fig. 2 below.

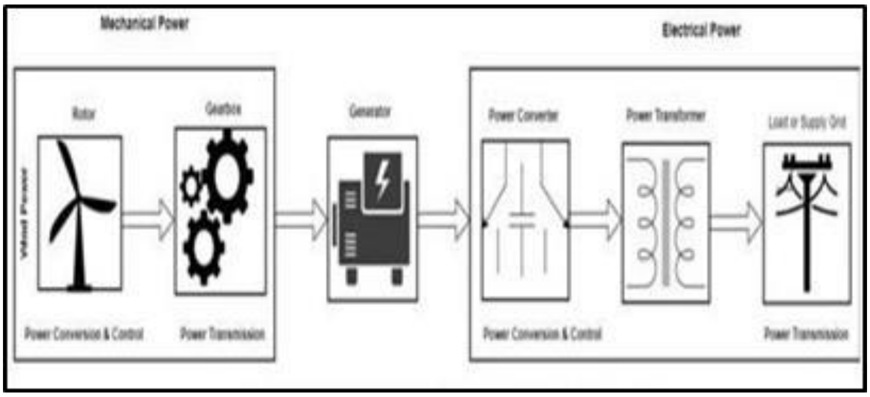

Fig. 2: Working of a wind energy system power plant

IV. Wind power calculation[2]

The probability density function of a Weibull random variable is:

$$f(x;\,\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} & x \geq 0 \\ 0 & x < 0 \end{cases} \qquad (1)$$

The Betz law provides the following equation for theoretical wind power-

$$P_{wind}(t) = \frac{1}{2}\rho S v_1^3(t)\left\{1 - \left(\frac{v_2(t)}{v_1(t)}\right)^2 + \left(\frac{v_2(t)}{v_1(t)}\right) - \left(\frac{v_2(t)}{v_1(t)}\right)^3\right\} (2)$$

Simplified Maximum Theoretical Wind Power:

$$P_{wind}(t) = \frac{1}{2}\rho S v^3(t) \qquad (3)$$

Where v_1 (t) represents the speed of the rotor upstream, v_2 (t) represents the speed of the rotor downstream, and v (t) represents the speed of the fluid power device. The surface area of turbine A_1 is S. The area of fluid before and after the turbine is A2, and the density of air is 1.23 kg/m3.
If we differentiate p wind (t) wrt v_2 (t)/ v_1 (t).
The result is:
Pwind reaches maximum value when
v_2 (t)/v_1 (t) = ⅓
Substituting this value in these results,

$$P_{wind}(t)_{max} = \frac{16}{27}\cdot\frac{1}{2}\rho S v^3(t) = C_p\cdot\frac{1}{2}\rho S v^3(t) \qquad (4)$$

Where Cp is called Coefficient of Performance. It has a maximum of Cp (max)=0.593 or 59.3% which is also known as the Bent'z limit.

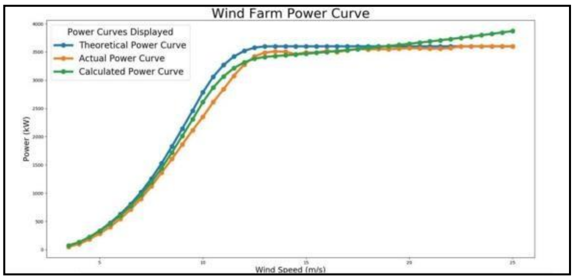

Fig.3 Wind farm power curve [2]

According to Bent'z law, wind turbine can never be better than 59.3% efficient. The law states that the maximum power generated by wind is independent of the design of wind turbines. The law can be explained by considering that if all of the energy coming from wind movement into the turbine were converted into useful energy then the speed of wind afterwards would be zero.

Nevertheless, if the wind stopped moving at the exit of the turbine, then no fresh wind could enter - it would be blocked. The improved equation for theoretical wind power is:

$$P_{theoretical}(t) = \frac{1}{2}C_p N_g N_b \rho S v^3(t) \qquad (5)$$

Where ρ is air density in kg/m^3, S = rotor swept area in m^2, v (t) denotes wind velocity in m/s, C_p is coefficient of Performance, Ng denotes generator efficiency, N_b is gearbox bearing efficiency.

Most of the research already done in the field of wind Power Generation provides a good insight into the theoretical Wind Power, but the actual wind power although being, close to the Theoretical curve has no definite formula to date. From the dataset of the wind farm we fitted a positive coefficient polynomial Lasso Regression Curve to the dataset and obtained the following empirical expression:

$$P_{actual}(t) = \alpha \times P_{theoretical}(t) + \beta \times v^2(t) \qquad (6)$$

$$P_{actual}(v(t)) = \frac{\alpha}{2} C_p N_g N_b \rho S v^3(t) + \beta \times v^2(t) \qquad (7)$$

The value of the constraint obtained were α = 0.9013(dimensionless) and β= 0.7172kg/s.

This gives us more intuition about the instantaneous power delivered by the turbine at a given point of time. Fig 3 shows the fitted regresion curve, which is the good approximation for the actual power for wind speed values between 0-20m/s. One of the limitation of this curve is that the value of P_{actual} (t)= $P_{theoretical}$(t) for wind speed v(t) >20m/s . Furthermore, the obtained coefficients tells us that the actual powercomprises of approximately90% Theoretical power and 72% Squared wind speed as seen in fig. 4.

Moreover, the Power loss which leads to the derivation of the actual wind power from theoretical wind power can be calculated as follows:

$$Loss\ (\%) = \frac{P_{theoretical}(t) - P_{actual}(t)}{P_{theoretical}(t)} \times 100\%$$

$$= \frac{\frac{1}{2} C_p N_g N_b \rho S v^3(t) - (\frac{\alpha}{2} C_p N_g N_b \rho S v^3(t) + \beta \times v^2(t))}{\frac{1}{2} C_p N_g N_b \rho S v^3(t)} \times 100\%$$

$$Loss\ (\%) = \left\{(1-\alpha) + \frac{\beta \times v^2(t)}{\frac{1}{2} C_p N_g N_b \rho S v^3(t)}\right\} \times 100\% \qquad (8)$$

As $\frac{\beta}{\frac{1}{2} C_p N_g N_b \rho S v(t)} \ll 1$, ignoring the second term, we get,

$$Loss\ (\%) \cong (1-\alpha) \times 100\% = 9.87\% \qquad (9)$$

This power loss of 9.87%plausibly occurs due to frictional forces, wind turbulence disturbances, wake effect, and other environmental effects. This numerical value gives an approximate estimation of these losses combined together.

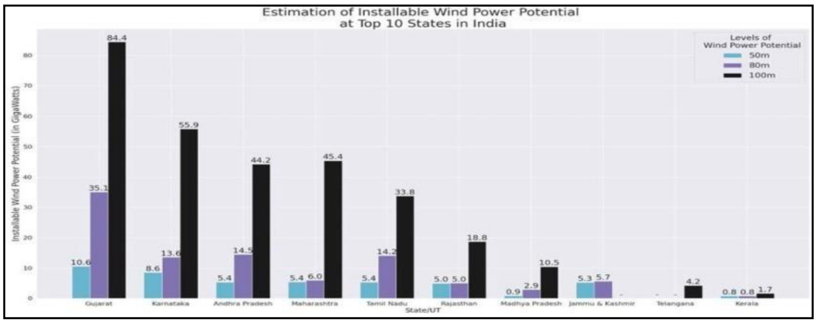

Fig. 4: Estimation of Installable Wind Power Potential at top 10 states in India

V. Wind Turbine

A wind turbine consists of the following major components: a tower, nacelle, and rotor. With the wind turbine's blades shaped like airfoils, wind energy is captured and transformed into rotational energy. By means of the high-speed shaft, the low-speed shaft drives the generator, while the gearbox increases its rotational speed by driving the rotor [1]. The gearbox, high-speed shaft, generator, and part of the low-speed shaft are all contained in the nacelle. It is possible to have variable or fixed speed wind turbines as seen in fig. 5. Variable speed turbines are more efficient for longer periods of time yet require electric power processing in order for feeding electricity into the electrical grid at the proper rate.

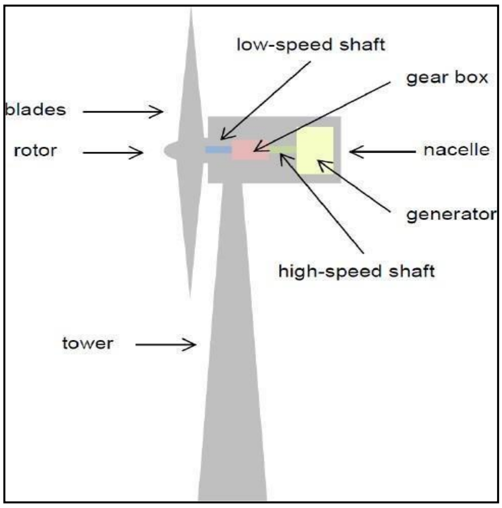

Fig. 5: Wind Turbine Block Diagram

WT Power output-

The power obtained from WT is denoted by symbol C p and it is called power co-efficient.

$$Pm = Cp\frac{1}{2}\rho A\upsilon^3 = CpPm - W \qquad (1.1)$$

R: radius of blade [m], υ: wind velocity [m/s], Pm: Power extraction, ρ: air density [kg/m3], Co-efficient of power: C p, C p is a function of tip speed ratio and blade pitch angle, where tip speed ratio is defined as:

$$\lambda = \frac{R\omega}{\upsilon} \qquad (1.2)$$

ω angular velocity of WT in rad/s, The ω is calculated from the speed n (Rev/min) by

$$\omega = \frac{2\pi n}{60} rad/s \qquad (1.3)$$

$$Cp = \frac{1}{2}(\lambda - 0.022\beta^2 - 5.6)e^{-0.17\lambda} \qquad (1.4)$$

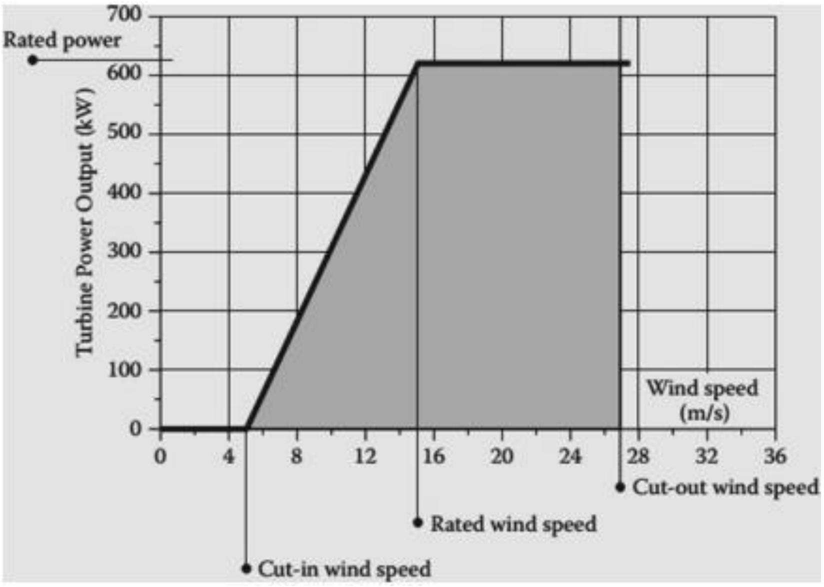

Fig 6: WT Power curve showing three different speeds [3]

Advantages of Variable speed turbines-

- Because of technological advancements in generators and power electronics, variable-speed turbines are more cost-effective and more popular at the utility level than constant-speed turbines.
- By having the rotor operate at a variable speed, the turbine loads can also be reduced since sudden increases in wind energy caused by gusts can be absorbed by the rotor speed rather than bent components.
- In addition to variable pitch and variable pitch wind turbines, fixed pitch and fixed pitch wind turbines may also be available. I.e., the blades may or may not be able to rotate about their longitudinal axes.
- Variable-pitch turbines may have some or all of their blades rotate along the pitch axis.
- Fixed pitch machines are cheaper to build however, the ability of variable pitch turbines to reduce loads and control aerodynamic torque has propelled their dominance.

VI. Power Curve-

In this case, the turbine's mechanical power is related to the wind speed. Data from the manufacturer on the power curve confirms that the wind turbine performs as stated. A power curve consists of three zones: cut-in, rated, and cut-out wind speeds [12]. In cut-in wind speeds, wind turbines barely begin to work and produce electricity. Nominal power is produced at a rated speed, which is also the rated output power of the generator. Cut-out speed refers to the maximum speed at which a turbine may operate; exceeding this speed will cause excessive damage to the turbine. As the wind speed increases, the captured power increases proportionally.

VII. CONCLUSION

The analysis presented in this article may be useful for future studies that include integration and expansion of renewable energy into existing power grids, cost-benefit analysis, and revenue analysis of renewable energy integration.

This paper shows the generation of electricity through a renewable source of energy that is wind energy. Wind energy is the most rapidly growing green industry and will be a great source of renewable energy for the globe in the near future. In this paper, we have tried to study how the generation of electricity from a wind turbine takes place in a simpler way. We have also taken an approach towards the equation used to calculate this wind energy and use it according to our benefits. As the existing sources of electricity are on the verge of extinction, this renewable source of energy can emerge as a promising source of electricity if utilised efficiently. We have also studied wind turbine generators in detail and how it plays a crucial role in the generation of electricity through wind energy.

REFERENCES

[1] Ateeq ur Rehman, Zahid Wadud, Rajvikram Madurai Elavarasan ,Ghulam Hafeez, Imran Khan (Senior Member, IEEE), Zeeshan Shafiq and Hassan Haes Alhelou(Senior Member, IEEE)-An Optimal Power Usage Scheduling in Smart Grid Integrated With Renewable Energy Sources for Energy Management.

[2] Farhan Hai Khan,Tannishtha Pal, Bishal Kundu- Wind energy- A practical power analysis approach

[3] Iram akhtar, Sheeraz Kirmani and Mohammed Jameel-Reliability Assessment of Power System Considering the Impact of Renewable Energy Sources Integration Into Grid With Advanced Intelligent Strategies

[4] Ateeq ur Rehman , Ghulam Hafeez, Fahad R. Albogamy, Zahid Wadud, Faheem Ali , Imran Khan , (Senior Member, IEEE), Gul Rukh , and Sheraz Khan- An Efficient Energy Management in Smart Grid Considering Demand Response Program and Renewable Energy Sources. Kishor V. Bhadane,Tushar Jaware,Anand Nayyar-Wind Energy System Grid Integration and Grid Code Requirements of Wind Energy System

[5] K. Ma, T. Yao, J. Yang, and X. Guan-Residential power scheduling for demand response in smart grid

[6] N. Javaid, G. Hafeez, S. Iqbal, N. Alrajeh,M. S. Alabed, and M.Guizani-Energy-efficient integration of renewable energy sources in the smart grid for demand-side management

[8] Gökhan Erdemir, Aydın Tarık Zengin, Tahir Cetin Akinci-Short-term wind speed forecasting system using deep learning for wind turbine applications

[9] Bishwajeet Pandey- Wind Energy: A Review Paper

[10]Shuran Liu, Member, IEEE, and Konstantinos Kopsidas, Senior Member, IEEE- Shuran Liu, Member, IEEE, and Konstantinos Kopsidas, Senior Member, IEEE

[11]Xue Lyu, Member, IEEE, Youwei Jia, Member, IEEE, Tao Liu, Member, IEEE, and Songjian Chai, Member, IEEE :System-Oriented Power Regulation Scheme for WindFarms: The Quest for Uncertainty Management

[12]F. Blaabjerg Aalborg University , Ke Ma Shanghai Jiao Tong University : Wind Energy Systems

[13]A. Prasai, J.-S. Yim, D. Divan, A. Bendre, and S.-K. Sul, "A new architecture for offshore wind farms," IEEE Trans. Power Electron [14]C. Meyer, M. Hoing, A. Peterson, and R.W. De Doncker, "Control and design of DC grids for offshore wind farms," IEEE Trans. Ind.

[15]Z. Chen, J. M. Guerrero, and F. Blaabjerg, "A review of the state of the art of power electronics for wind turbines," IEEE Trans. Power Electron.

[16]W. Chen, D. Xu, N. Zhu, M. Chen, and F. Blaabjerg, "Control of doubly-fed induction generator to ride-through recurring grid faults," IEEE Trans. Power Electron

[17]A. D. Hansen, F. Iov, F. Blaabjerg, and L.H. Hansen, "Review of contemporary wind turbine concepts and their market penetration,"

[18]S. M. Muyeen, R. Takahashi, T. Murata, and J. Tamura, "A variable speed wind turbine control strategy to meet wind farm grid code requirements," IEEE Trans. Power Electron.

[19]S. Müller, M. Deicke, and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines," IEEE Ind. Appl. Mag

[20]Z. Chen, J. M. Guerrero, and F. Blaabjerg, "A review of the state of the art of power electronics for wind turbines," IEEE Trans. Power Electron

[21]N. Balu, T. Bertram, A. Bose, V. Brandwajn, G. Cauley, D. Curtice, A. Fouad, L. Fink, M. G. Lauby, B. F. Wollenberg, and J.N. Wrubel, ``On-line power system security analysis," Proc. IEEE,

[22]V. Nelson,Wind Energy: Renewable Energy and the Environment, 3rd ed., Broken Sound Parkway NW: Boca Raton, FL CRC press

[23]Zhao, D.M., Zhu, Y.C. also, Zhang, X. (2011) Research on Wind Power Forecasting in Wind Farms. Procedures of the 2011 IEEE Power Engineering and Automation Conference, Wuhan,

[24]H. Holttinen et al. "Outline and Operation of Power Systems with Large Amounts of Wind Power, first aftereffects of IEA joint effort",

[25]A Review of Wind Energy Scenario in India, International Research Journal of Environment Sciences, ISSN 2319– 1414

[26]S. A . Vargas, G.R.T.Esteves,P.M. Macaira, B. Q. Bastos, F.L. Cyrine Oliveria and R.C. Souza," Wind power generation; A review and a research agenda," J. Clean. Prod